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Design, Development and Testing of a Recovery System for the Predator™ UAV

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Abstract

This paper presents the design, development and testing of a recovery system for the emergency flight termination of an 1,800-pound air vehicle, the General Atomics Aeronautical Systems (GA) Predator™ Medium Altitude Endurance Unmanned Air Vehicle (MAE-UAV). The project was on a very tight schedule; to maximize speed and efficiency, the system was designed using computers; all information exchange (including manufacturing patterns) between the engineering efforts, separated by 3,000 miles, was electronic. A particularly efficient main parachute canopy was developed with very good stability and in excess of 100 ft^2 of drag area per pound of canopy. The project also required the manufacture of a new drop test vehicle (with attendant ground and aircraft handling equipment) and an instrumentation and data collection system. The design, test hardware manufacturing, and testing phases were finished in 72 days; the entire program, including delivery of five "production" systems, was completed in 132 days.

Project Scope and Schedule Overview

The entire Predator™ UAV program was on a very aggressive schedule (contract in November '93 with first flight in July '94) which, of course, affected the sub-system suppliers. The actual work was initiated on 7 April '94, and the design and manufacture of the ground and air drop test recovery systems, the complete air drop test vehicle (with instrumentation and control systems), the ground and aircraft handling equipment, and the ground and air deployment tests themselves, were completed by 18 June '94 (72 days total).

One of the authors provided engineering and design support from the East Coast, while the remaining engineering and all manufacturing took place at the BPS facility in California. The use of computer design technology and electronic transfer of data (including patterns, which were then plotted at full scale) made this possible, and furthermore accelerated the project's pace: telecommuting was far faster than physical commuting, and when revisions were necessary, they were handled within hours. The entire recovery system program, including delivery of five "production" systems, was completed by 19 August '94 (132 days total).

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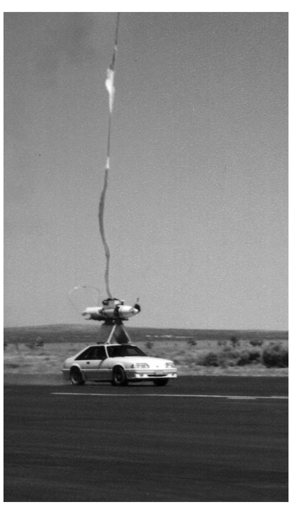
System Description

The Predator™ UAV (Figure 1) is a relatively small aircraft constructed of high strength composite materials of various types. The wings and tail surfaces are removable and the entire vehicle fits into a purpose built container, several of which can be transported in a C-130 along with the ground control trailer.

Figure 1: *The Predator™ UAV*

The Predator™ has a pusher prop, which requires the use of a force deployment method to ensure that the parachute will clear the prop. A tractor rocket system was selected for a crosswind deployment of the main parachute; a 60" pilot chute is also used to keep the canopy under tension as it blows downwind. A very rugged intermediate riser was constructed of multiple layers of Kevlar to prevent the prop from cutting through the riser should the two come in contact with the prop still turning. After burnout, the rocket motor is released from the extraction bridle and falls free (during the air drop test, there was minor damage to the canopy, apparently caused by the rocket motor). Figures 2 and 3 show the rocket, bridles, pilot chute and canopy during the ground based deployment test.



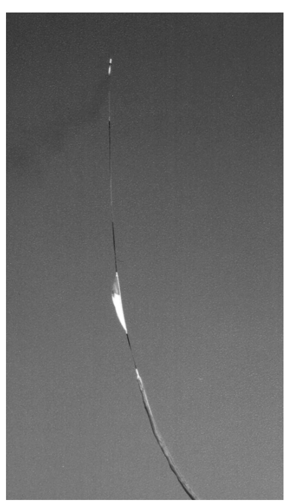


Figure 2 and Figure 3: *Ground-based deployment test.*

The parachute compartment is aft of the fuel cell (which straddles the CG) and sits on top of the main landing gear well, which results in a rather odd shape with a variety of bumps and angles. The parachute compartment cover is made of two very light layers of fiberglass over balsa wood held to the vehicle with tape (see Figure 1). The cover will shatter as the rocket motor punches through it; the pieces are very light and will blow downstream and not interfere with the parachute deployment (see the debris visible in Figures 2 and 3, showing the ground deployment test).

The structural limitations of the UAV (6,000-pound limit load to riser attachment) and GA's desire to prevent wild gyrations of the vehicle during the parachute deployment required that we develop a system to recover the vehicle on the two rear risers, which are attached above and slightly aft of the center of gravity. The vehicle will have about a 30-degree nose-down attitude on the two rear risers during the initial recovery. After a time delay of 15 seconds from rocket initiation, the rear risers are released (electrically initiated pyrotechnics) and the "transition risers" (attached to the same riser fixture) stretch out an additional 46". This allows the single front riser to become taut as the vehicle transitions from a 2-point to 3-point suspension at an approximately level attitude. Figure 4 is a sketch of the riser configuration.

All of the hardware and parts required for the riser attachments and the transition and ground release mechanisms were designed and manufactured by BPS. Figure 5 shows the rear riser fitting bolted to the airframe (note that the bolts go through the carbon skin to the aluminum landing gear frame). The requirement to design and build this hardware was added about seven weeks into the program and caused some slight delay of the final deliveries but never adversely affected the program schedule.

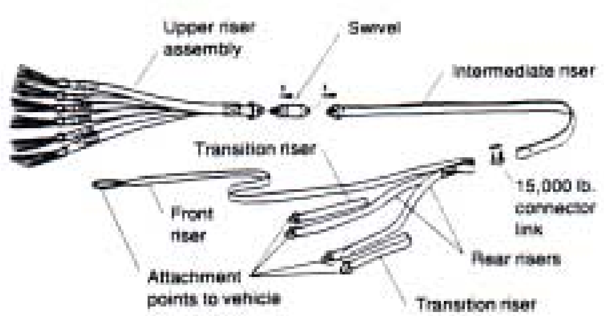


Figure 4: *Riser configuration*

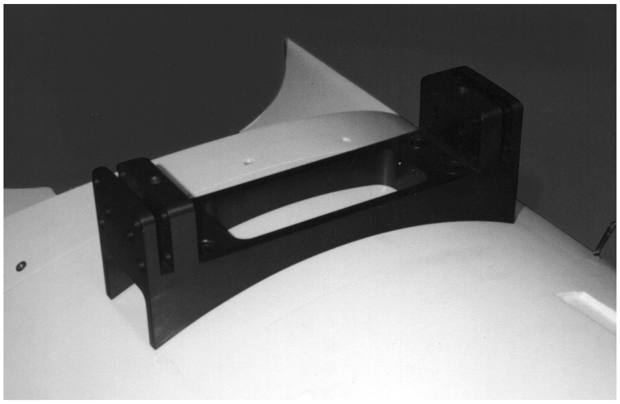


Figure 5: *Rear riser attachment fitting.*

Analysis and Design of Recovery System Components

Performance Requirements

The contract required the main canopy to provide a rate-of-descent of 18 ft/sec at 4,000' MSL with 1,800 pounds suspended weight; the total system weight/volume allowance (inclusive of the rocket motor and launch tube, but exclusive of riser mounting hardware, ground release mechanism, etc.) was 80 pounds in 2.2 cubic feet. The system was actually tested at 1,875 pounds gross weight. Opening shock was limited to 6,000 pounds to the vehicle through the rear riser attachment.

Note that the "production" systems actually weigh less than 68 pounds for the components counted against the 80 pound allowance; the riser release mechanisms, lower riser assemblies, etc. add approximately 8 pounds to the total.

Tractor Rocket/Extraction Components

Based on rough estimates of the canopy weight, an existing rocket motor design (160 lb-sec total impulse; 90 lb average thrust) was selected and ordered during the first week of the project. The manufacturer's thrust-time curves were used to design the extraction system components. Again, the short timeline and the limited budget of the project did not allow the development of detailed models of the deployment loads. Therefore, a variety of methods were employed to conservatively estimate upper limits for loads in the structural members. The simple models chosen were clearly at variance with the physical realities of the deployment scenario, but they were selected to predict loads in excess of any that might actually be obtained (*e.g.*, the assumption of constant acceleration of the rocket/bridle system, ignoring the growing mass of the extracted portion of the deployment bridle, yielded higher separation velocities and thus higher snatch loads than the actual constantly decreasing acceleration would). The limits thus calculated were then used to establish minimum material strengths or (in many cases) to validate the choice of materials based on availability or other criteria. While this methodology led to the use of stronger materials than actually required, it also produced a robust system at a much lower cost than otherwise obtainable.

As shown in Figure 6, the extraction system con-

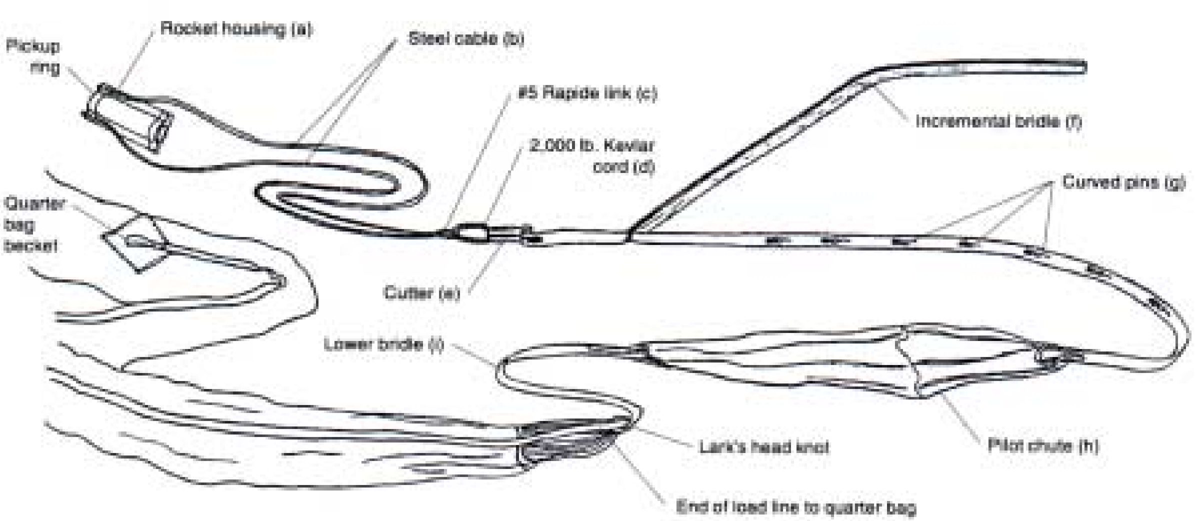


Figure 6: *Extraction system.*

sists of: the rocket motor [inside housing (a) in sketch]; a steel cable bridle (b) attached to the pickup ring around the rocket motor; a #5 Rapide link (c) with a Kevlar loop (d) and a cutter (e) to release the rocket motor after burnout; the incremental bridle (f); the bridle section with curved pins (g) attached for pack closure; the pilot chute (h) with bridle running up through the center; and the lower section of the bridle (i). Note that the bridle is continuous from the Kevlar connector loop to the lark's head attachment to the canopy vent lines. Note also that the lark's head on the end of the bridle also captures the load tape that runs down the canopy to the quarter bag closing becket.

The use of a tractor rocket contained within the flight vehicle also required the design of a launch tube, mounting brackets, and load pickup ring. The launch tube system directs the exhaust gases upward and out of the vehicle and prevents damage to the vehicle and the recovery system during the launch. These components mount to the forward bulkhead of the parachute stowage compartment and also count against the weight and volume allowance for the recovery system.

The design of the rocket motor launch tube was significantly complicated by an "oh, by the way" requirement that the motor must be easily removable from the vehicle without affecting the parachute rigging. This is accomplished by reaching up from the bottom of the vehicle through the wheel well to remove an electrical connection and three #10-24 screws that hold the bottom cover of the tube in place; the rocket can then be slid out of the bottom of the fuselage. Since the rocket motor is a slip fit into the pickup ring and the steel cable bridle is attached to the pickup ring and not to the rocket motor itself, all of the rigging for the extraction system can remain in place as the motor is removed. All components of the rocket motor launch tube/mount were designed and built by BPS specifically for this project.

Quarter Bag and Stowage Container

The projected mass of the main parachute and the decision to use a tractor rocket for deployment, compounded by weight and volume limitations and the irregular shape of the stowage compartment, led to the choice of a quarter bag and sacrifice panel for deployment control. A fabric stowage container was dictated by the tight schedule and budget: no time or funding was available for construction of a rigid container. A fabric container also provided cover flaps, which could protect the deploying parachute from the relatively sharp edges of the hatch. It further allowed the easy installation of beckets for quarter bag retention ties.

Patterns for the quarter bag and container were developed using CAD software. The three-dimensional configuration of the container, for example, was dictated by the available volume with allowances for installation clearance and pack growth following its removal from the transfer container. This 3-D solid was "unfolded" to form the two-dimensional pattern surfaces, to which were added seam allowances, reinforcing, and other similar modifications.

Because all development had taken place in the CAD environment, changes were very easy to make. Portions of the CAD drawings were also exported to desktop publishing software, where they were annotated for use in the manufacturing and packing instructions.

The quarter bag design features an internal anti-slump flap and line stow flutes, both chosen because of the high accelerations and onset rates associated with the tractor rocket extraction. A load tape from the closing becket of the quarter bag up to the extraction bridle is used to pick up the mass of the packed quarter bag, and also helps prevent damage to the canopy during extraction. Figure 7 shows the packed quarter bag.

Figure 7: *The packed quarter bag.*

To keep the schedule, the quarter bag had to be designed before the first main parachute was completed. Therefore, a parachute linear mass distribution was calculated from the known properties of the nylon materials and the pattern dimensions; with suitable assumptions about the packing techniques, this mass distribution allowed accurate prediction of the packed bulk. A quarter bag is typically designed to tightly fit the parachute canopy,[1] but for this application the bag had to bend into an S-shape to follow the convoluted floor of the compartment. To soften the quarter bag, we sized it to fill the entire floor. Flutes for suspension line stowage covered the front and part of the back of the bag. Despite its size, it was still relatively stiff when packed.

The stowage container was made from webbing-reinforced nylon pack cloth and featured large, protective side and end flaps. The side flaps were designed with extra slack for ease of packing, and tightened with laces at the end of the pressure-packing cycle. They were closed by a series of nylon loops, locked with stainless steel curved pins attached to the lower end of the tractor rocket extraction bridle.

The available parachute system volume, with adequate allowance for installation and pack growth, was approximately 1.6 cubic feet; the weight of the parachute materials to be packed into this volume was 70 pounds. The resultant pack density of over 43 lbs/ft^3 was over the limits of pneumatic presses, so a hydraulic press was chosen.[1] A specific pressure on the order of 90 psi was projected;[2] the possibility of higher pressure requirements was anticipated, since the compartment shape was not conducive to efficient pressure packing, and since the lower portion of the parachute would be contained in the relatively inflexible quarter bag.

Because multiple systems were to be packed and stored, it was logical to separate the functions of packing and storage fixtures. We therefore designed an inexpensive wooden transfer container (to control "growth" of the system after removal from the packing fixture), and reinforced it with a single, heavy-duty, metal packing fixture during the actual packing phase. Each system was heat-stabilized in the transfer container, to further control growth. This allowed multiple systems to be packed without an investment in multiple metal fixtures. Figure 8 shows the packed recovery system, inside the transfer container.

Figure 8: *The packed recovery system in its transfer container.*

The transfer container was also designed to be attached to the air drop test vehicle, where it served the additional role of an inexpensive mockup of the Predator™ parachute compartment for the drop tests.

Main Canopy

The main canopy developed for this project is a scaled-up version of a personnel parachute canopy that BPS had previously developed and sold. It is an extended skirt, modified tri-conical made of 0-3 CFM cloth; meshed drive vents arranged asymmetrically cause the parachute to turn slowly (about 1.5 minutes per revolution) to prevent flying off of the test range. This design has a modest glide ratio with outstanding stability and provides in excess of 100 square feet of drag area per pound of canopy. The main canopy uses single stage reefing to limit riser loads to 6,000 pounds at 120 KIAS.

Using performance data from one of our personnel parachutes of 500 ft^2 (C_d 1.3) and not knowing what to expect from scaling up by a factor of nine, we made extremely conservative performance calculations during the preliminary design phase of the contract negotiations. This was fortunate because we were able to negotiate a fairly large pack volume (which still required pressure packing) and a reasonable weight allowance.

Based on our estimate, we sized the first two canopies (for testing) at 77.7' nominal diameter. The actual measured performance (C_d 1.47) of the main canopy was so much better than estimated that the production canopies were made significantly smaller (70.5' nominal diameter) than the test articles, yet they still meet the contract requirements at a higher weight (1,900 *vs.* 1,800 pounds). The weight of the 70.5' canopy and lines is 51.8 lbs and it has a drag area of 5,739 ft^2, yielding a canopy efficiency of approximately 110 ft^2 of drag area per pound of canopy.

Test Program

Air Drop Test Vehicle

The test vehicle was fabricated in-house starting with a 175 gallon propane tank and adding on fixtures and fittings as needed to accommodate the various equipment installed (a true "boilerplate" parachute test vehicle). The empty weight of the test vehicle is about 700 pounds with a water capacity of about 1,400 additional pounds. The vehicle was handled and controlled in the aircraft with a large roller track system arranged in a "V." Vertical motion of the test vehicle relative to the aircraft was controlled with a 3" I-beam welded to the underside of the vehicle with small rubber capture rollers (on the structure of the track system) to prevent the lower flange from moving upward while in the aircraft.

In order to load the vehicle into the drop aircraft (CASA 212-100), we modified a flat bed utility trailer by welding 2" square steel tubes at each corner to receive and stabilize 48" lift jacks. The test vehicle was loaded onto the trailer with a chain hoist and positioned on a section of roller conveyer track, then strapped down for transport to the ramp. Once in position behind the aircraft tailgate, the trailer was disconnected from the tow truck and the corner jacks were attached. We were then able to raise the trailer bed gradually (while keeping it level) in 1" increments until it was even with the V-track roller rack in the aircraft (Figure 9). The aircraft loading jacks were also in position to prevent the deck of the aircraft from dropping as the weight of the test vehicle was transferred onto the aircraft from the trailer. The test vehicle was then pushed into the aircraft to the forward limit of the track (the test vehicle CG falls on the aircraft CG when in this position) and strapped down (next time we'll have a powered winch to help with this part). Figure 10 shows the test vehicle in the aircraft just before takeoff.

During flight as we set up for the test drop (after the ramp was dropped and leveled), the vehicle was incrementally moved aft on the track, with the aircraft trimmed and stabilized after each small movement. We were able to move the vehicle all the way to the aft end of the tailgate and achieve a level deck angle at the target airspeed (90 KIAS) and altitude (7,500' MSL) by varying flaps and trim. After a dry run, the test vehicle was extracted from the aircraft with a 9' diameter ribbon drogue that we had on hand from a previous program. Figures 11 and 12 show portions of the extraction sequence taken from the video tapes.

Figure 9: *Loading the test vehicle into the aircraft. The trailer has been raised on its jacks to the level of the V-track roller in the aircraft.*

Figure 10: *The air drop test vehicle installed on the aircraft roller track, just before takeoff.*

Figure 11: *The extraction parachute just after inflation.*

Figure 12: *The test vehicle just after extraction.*

Video/Data/Instrumentation/Control System

The instrumentation system was based on a 486SX/33 sub-notebook computer with a 120 MB hard disk drive and a 5-MB PCMCIA "credit card" memory system. An analog to digital to parallel converter was used to accept data from the riser load cells and the pressure sensor. Appropriate conditioning circuits were used and the entire system was calibrated prior to use.

The timing and control circuit for firing the rocket and starting the data system was also constructed in-house. It used two completely redundant delay/firing circuits to initiate the rocket deployment (one started the entire system for data/control, the other only fired the rocket if the first failed). Both firing circuits were initiated with a pin pulled by a static line as the nose of the test vehicle cleared the aircraft. All circuits were shunted to ground when not in use and the rocket itself was physically blocked and held in the breach by a clamp assembly that was removed a few minutes prior to drop.

The test vehicle had two 8mm camcorders mounted on board and the drop was also video taped from the tailgate of the drop aircraft, the ground and two chase planes. Selected frames from the drop test video are shown in Figures 13 through 16.

All of the electronic systems were built in-house from standard parts and components. The total cost of the parts purchased for the control and instrumentation system was about $8,000. Data was gathered for the riser loads and pressure *vs.* time; the pressure data was later converted to altitude and rate of descent and plotted against time. These plots are shown in Figures 17 and 18.

Figure 13: *On-board video frame of tractor rocket at bridle extension.*

Figure 14: *Main parachute just after extraction from the quarter bag.*

Figure 15: *Main parachute approaching reefed inflation.*

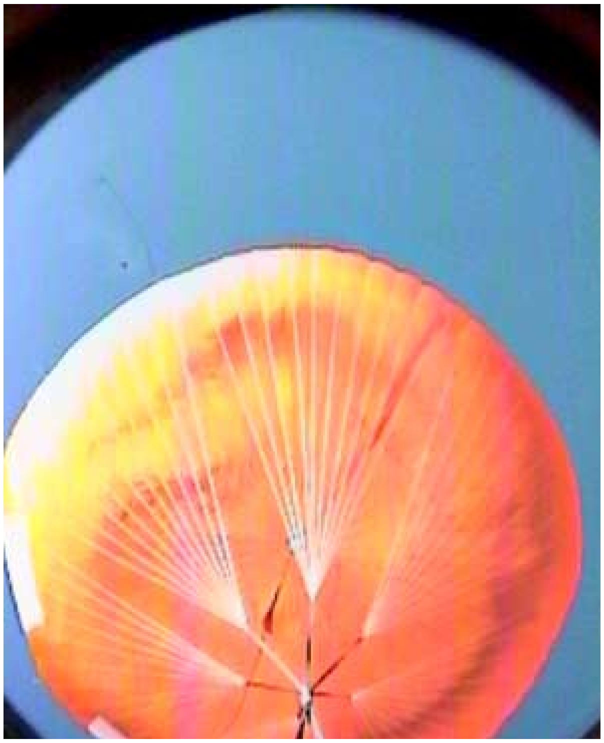


Figure 16: *Main parachute at full inflation.*

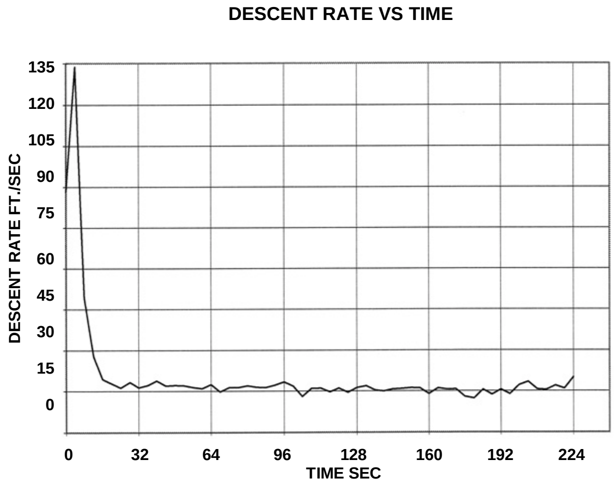


Figure 17: *Descent rate vs. time.*

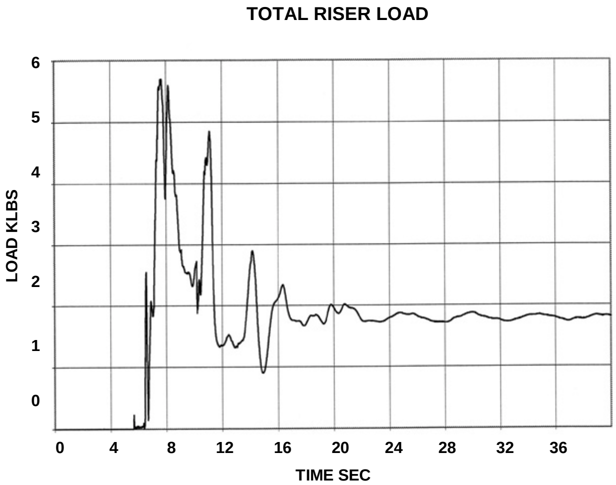


Figure 18: *Total riser load vs. time.*

Lessons Learned

- We needed someone with the primary responsibility of photo documentation of the entire project from start to finish.
- We needed an extra photographer in the airplane.
- We needed an extra photographer on the ground.
- We should have mounted a camcorder on the roof the airplane to record the extraction and exit events.
- We needed another camcorder and a motor drive 35mm camera (with a fish eye lens?) on the test vehicle.
- It would be nice to have high-speed motion picture camera on the test vehicle, but it is not essential as the video provides adequate information for review and analysis of the events. However, film is still much better for presentation purposes.
- Camcorders on the test vehicle need to be set up with remote on/off and easily visible means of verifying operation—perhaps a switchable monitor in the aircraft?
- More radios are needed for the test crew and a better intercom is needed in the aircraft with everyone on line and able to transmit/receive on the radio net.
- We need a better way to locate the test vehicle and various components on the ground after the test (perhaps a map overlay with grid?). Even in the desert it's hard to find things like the extraction drogue.
- The camera mounts on the test vehicle need to be easier to load/service and the instrumentation package needed easier access, some provision for cooling and a higher capacity battery charging system.
- The test vehicle needs a releasable shackle on the nose for ease of handling, and we need winch systems in the aircraft and on the trailer to ease the handling of the test vehicle.
- We needed 60 days more time than we had.
- We should have negotiated a bonus based on weight savings.

Table 1

Production System Component Weights

Canopy w/Load Line	51.80
Container	4.60
Quarter Bag	2.00
Pilot Chute/Extraction Bridle	1.60
Upper Riser w/Shackle	0.80
Swivel	1.80
Rocket Motor	1.67
Rocket Motor Housing	1.67
Cable Bridle	0.20
Total Weight System	67.21

Acknowledgments

We thank Brian Vargus, Electronic Technician at Butler Parachute Systems, Inc., for his outstanding effort in the development and construction of the test vehicle, instrumentation and control systems, as well as the packing fixtures and transfer containers.

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2. Knacke, T. W. *Parachute Recovery Systems Design Manual*. Para-Publishing, Santa Barbara, CA, 1992.