DESIGN AND TESTING OF THE BQM-167A PARACHUTE RECOVERY SYSTEM

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Irvin Aerospace Inc, under contract to Composite Engineering Inc., has developed a recovery system for the Air Force Subscale Aerial Target (AFSAT) which is designated BQM-167A. AFSAT is a replacement for the ubiquitous MQM-107 and BQM-34 targets that have seen many years of service. The BQM-167A is an all composite aircraft with much higher weight and superior performance than the MQM-107 and consequently required a completely redesigned recovery system. The recovery system consists of a drogue parachute, main parachute, drogue retention system, drogue-to-main changeover system and a unique flotation system. The recovery system is designed to operate throughout the entire flight envelope, from pad abort to high altitude high-speed emergency recovery. This paper discusses the system modeling, recovery system design, system testing and test results conducted by Irvin Aerospace Inc. The paper details some of the unique features of the recovery system and some interesting lessons learned during the test program.

I. Introduction

In 2002, the USAF issued a requirement for a new subscale aerial target to replace the aging BQM-34 (Firebee) and MQM-107 (Streaker) systems that have been in service for several decades. Composite Engineering Inc. (CEi) of Sacramento, CA, was selected over two other bidders for the Air Force Subscale Aerial Target (AFSAT) program.

CEi's response included an all-composite aircraft, the Skeeter, was selected and subsequently became designated the BQM-167A. The AFSAT flight performance requirement includes high and low altitude operations, up to high subsonic Mach numbers. The requirement included the ability to recover the aircraft at all points in the flight envelope. Initial considerations were give to using existing, or modifications to existing, parachute recovery systems, but the wide flight envelope and higher recovered weights, at least compared with MQM-107, rapidly led to the conclusion that a new design parachute recovery system would be required. Moreover, due to the desire to keep the aircraft cross-section small, and minimize weight at the tail of the aircraft, the volume and weight criteria became key design drivers. As most parachute system designers have come to understand, the desirable requirements are maximum drag, with minimum weight and hence minimum installed volume, and, of course, low cost.

Figure 1. MQM-107 Recovery

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II. Prior History

Irvin had been the original designer of the MQM-107 parachute recovery system that has been in-service since the 1970's. This latter canopy was designed to set of key criteria, including an aircraft weight of 700 lb. However, by the time the MQM-107 had passed 25 years in service, it had blossomed to nearly 1400 lb, with no change to the original recovery system. One lesson learned, then, was to build in capability for aircraft weight growth as AFSAT can be expected to be in service for many decades.

In addition, the desire for system longevity is a key requirement from logisticians, but in practice, there are many factors that influence the life of a parachute system of a target, not the least of which are ground recovery damage, loss at sea and, the odd occasions where the target is actually shot down. Therefore, a typical lifetime of current systems is 5 to 7 recoveries, so designing for 10 'nominal' recoveries became a design objective.

III. Design Parameters

The essential minimum capability aircraft performance and recovery envelope is shown in Figure 2. The desirable (and actual) flight envelope is significantly larger than this minimum envelope, and the recovery system was desired to operate over the complete actual aircraft envelope.

The recovery system was intended to be operated in the same manner as the MQM-107 system, using the same Safe-Arm Device (SAD) and associated electrical outputs to control / initiate recovery system events, comprising tailcone removal, drogue-main handover and ground disconnect. The SAD concept of operation for the high altitude includes a barometric override to inhibit drogue-main handover until below an altitude of 10,000 ft. In all other recovery cases, the SAD provides a fixed time delay of 8 seconds between tailcone thruster initiation and the drogue-main handover signal. For pad abort, the ground control operator has the ability to override these functions and command main canopy release – this is used to shorten the drogue ride and get as much canopy out as soon as possible to recover the aircraft from low altitudes.

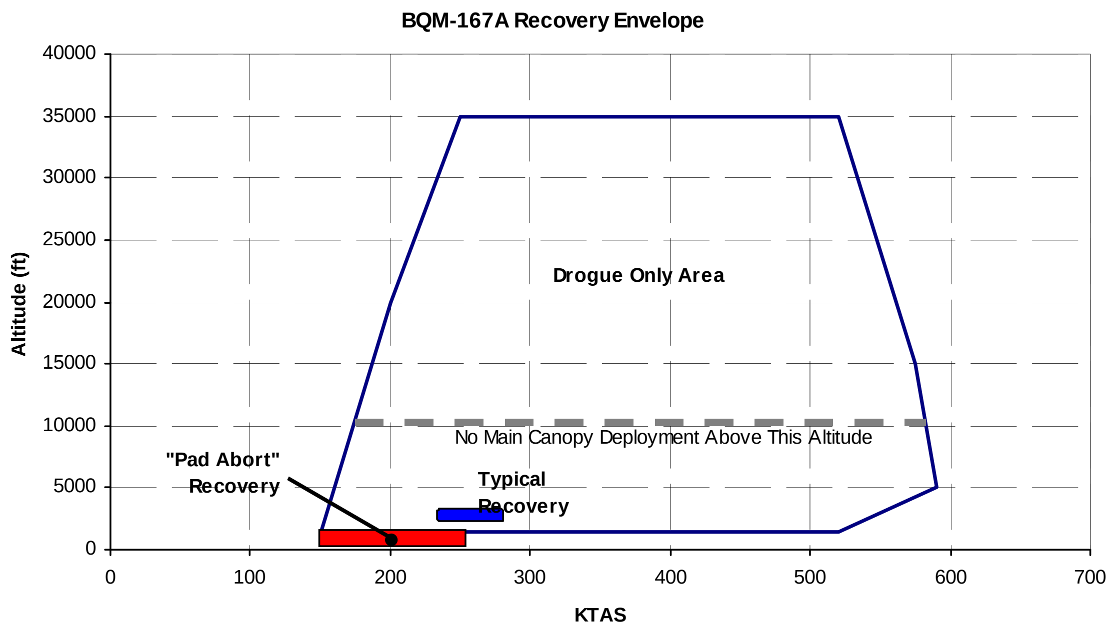

Figure 2. AFSAT Essential Minimum Recovery Envelope

The maximum recovered weight requirement was stated as 1750 lb, equivalent to a maximum ramp weight aircraft less the Rocket Assisted Take-Off (RATO) bottle and the fuel required to get to the corner of the flight envelope. The installation layout also reflected the MQM-107 arrangement, where thrusters using government-furnished cartridges are used to eject the tailcone. The energy imparted to tailcone is then used to deploy the drogue parachute, and then, at the commanded time, the drogue parachute is used to deploy the main parachute. The main and drogue parachutes are attached to a single point on the aircraft which incorporates a ground release.

IV. Design Trades

A. Drogue Canopy

The design trade for the drogue was limited in nature. Ribbon parachutes had been used with great success on many Irvin products and this canopy planform was the obvious choice. The design trades centered around the canopy size and whether the canopy needed to be reefed – the current MQM-107 drogue canopy is not reefed. Given a desire to bring the aircraft flight conditions to the 40 – 50 psf range for main canopy deployment, the drogue canopy size requirement was in the 9.5 – 10 ft D_o range. The TA-4J aircraft spin recovery parachute system, produced by Irvin in the 1960's, used a 9.85 ft D_o conical ribbon parachute that provided the ideal planform, and this was adopted for AFSAT.

Reviewing the load characteristics from the corners of the recovery system envelope made it very clear that the canopy would need to be reefed. Moreover, the canopy structural grid would need to be strengthened to accommodate the higher loads expected in the AFSAT application. This redesign effort took advantage of the advances in modern materials, and utilizes a Kevlar structural grid and Vectran suspension lines.

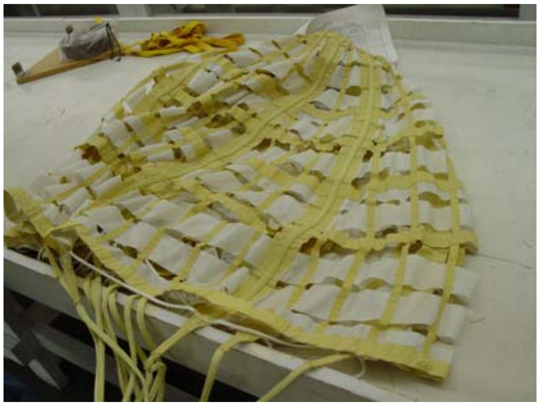

Figure 3. Conical Ribbon Parachute

B. Main Canopy

The main canopy design trades, again, were based around canopy planform, expected performance and, to a large extent, weight. Just prior to the AFSAT program, Irvin had participated in the Advanced Tactical Parachute System (ATPS) competition with a slotted polyconical parachute planform, Figure 4. During the ATPS program testing, the planform had shown great promise in terms of drag coefficient and stability. The design task was therefore to scale-up the canopy to a size appropriate for AFSAT, and, given the required range of descent velocities, this was determined to be 62.2 ft D_o, giving some 50% more canopy area than the MQM-107 system and a much higher drag coefficient.

A prototype of this canopy had also been designed under Irvin IR&D funding and had conducted some very limited testing, accomplished under the US Army Enhanced Recovery System (ERS) program. Concurrently, Irvin was also participating in two programs for the Japanese Space Agencies, now JAXA; the High Speed Flight Demonstrator (HSFD) and the Rocket Supersonic Transport (Rocket SST). The same canopy was adopted for all of these applications – the Rocket SST application using a cluster of three of these canopies.

Figure 4. Irvin XT-12 ATPS Canopy

Several design features were incorporated to keep the canopy weight to a minimum. A very low gore count / D_o ratio was selected, only 40 gores for the 62.2 ft canopy, and continuous Vectran suspension lines / radial structural members routed from Riser attachment point to the canopy vent ring and back down to the Riser attachment point. These features were necessary to keep the weight, and hence packed volume, to an acceptable level.

C. **Ancillary Components**

Two options were considered for routing the drogue parachute loads to the single attachment point; a bypass Riser, as had been used in Rocket SST, or using the main canopy deployment bag as the structural path, as in MQM-107. The latter was selected based on legacy MQM-107 experience, however, the drogue-main handover cutters were moved from the sides of the main canopy deployment bag to the front of the assembly to ease integration issues that were common with MQM-107.

D. System Baseline

The System Baseline, therefore, appeared relatively low risk, in terms of integrating existing components, simple strengthening of the drogue and scaling up of an already tested main canopy.

V. AFSAT Recovery System Testing

A. Main Canopy Development Tests

The main canopy development testing was completed on the concurrent programs and lessons read across to the AFSAT program. The canopy started out with a planform almost exactly a scaled-up version of the ATPS XT-12 canopy, but with reefing to control the loads. Given the benign nature of canopy characteristics measured during the ATPS program, scaling up was perceived as" low risk", and after one lightly loaded single canopy test, Irvin progressed to the Rocket SST three-chute cluster.

Reefing ratios had been determined based on published data for typical Ringslot parachutes. These first cluster tests showed opening loads far in excess of what would have been expected, and led to the loss of the first test vehicle. The program took the decision to step back from the cluster tests and characterize the single main canopy, as intended for the AFSAT program, in far more detail.

The initial canopy planform is shown in Figure 5. This construction comprises a Ringsail section in the lower gore region and a single large slot near the crown. Four gores also had cruciform mesh panels that contributed to the excellent stability characteristics.

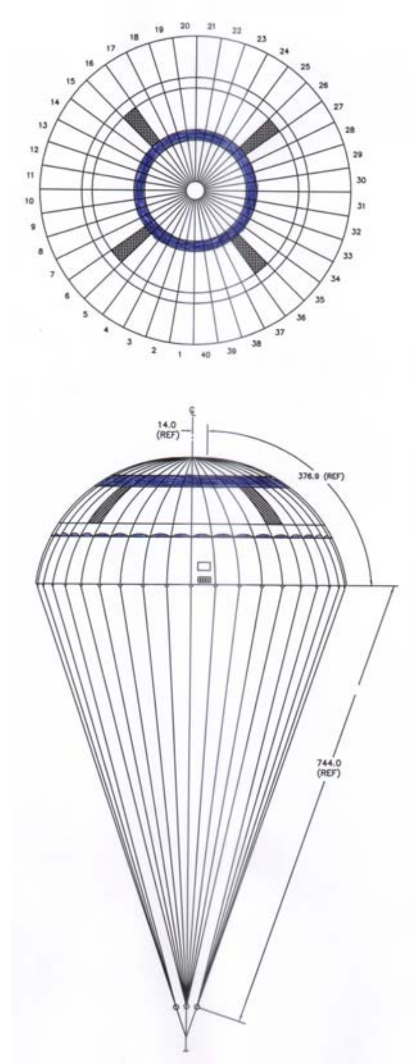

Figure 5. Initial Main Canopy Planform

Initial suspicions were directed at the reefing scheme, in that this was the only added feature compared with the XT-12 configuration. Mid-gore reefing rings were added, and single canopy tests were conducted with different reefing ratios in an attempt to characterize the reefing line length ratio with reefed drag area characteristics.

Testing showed, for the range of rather low reefing ratios tested, that the opening loads remained relatively constant and far in excess of what was expected. It became obvious that some other mechanism was 'at play' in this canopy. One further feature that had been added to the XT-12 planform were vertical tapes that spanned, separately, the large radial slot and between the panels above and below the sail. These vertical tapes were added to ensure even load transfer between panels.

The damage assessment after these tests showed that the vertical tapes across the large slot had been subjected to significant forces, pulling them outwards at their connection to the upper ring, as depicted in Figure 6. A consistent pattern of damage began to emerge.

Figure 6. Typical Vertical Tape Damage

Going back to the basic planform, the canopy can be considered as a mini disk-gap-band parachute. Looking at the video from these early tests, the initial deployment characteristics showed the crown region, i.e. above the slot, inflating very rapidly, leaving the remaining canopy flaccid. This corroborated the damage pattern where the vertical tapes appeared to have been pulled out.

If one assumed that the crown region was an ‘independent’ parachute, i.e. the crown inflation is achieved principally by airflow entering via the radial slot and not via the canopy mouth, the canopy inflation characteristics would be expected to be similar to a 20 ft D_o flat circular canopy. This assumption would lead to canopy loads in excess of the reefed loads and independent of the reefing ratio employed at the mouth of the canopy. This was exactly the same characteristics that had been observed in testing.

The question then became how to control the opening of the crown region. Several options were considered – reef the crown ‘ring’, close up the large slot to inhibit airflow, or add additional smaller slots in the crown region to control the opening loads.

The addition of reefing to the crown ‘ring’ was considered complex and relatively high risk, plus the high drag achieved early in the deployment sequence would greatly assist recovery under the AFSAT pad abort conditions. The concern with closing up the slot was that this would reduce the excellent stability characteristics of the canopy – as much landing damage on these types of aerial targets gets caused by the horizontal velocity due to canopy oscillation as occurs due to the vertical velocity. The consensus approach, therefore, was to add sufficient additional small slots to the crown region to control the opening loads.

The locations and sizes were determined by careful review and assessment of many published works. The introduction of two small slots was agreed, as depicted in the revised planform in Figure 7, and tested. The effects on the parachute opening load characteristics were immediate and profound. The canopy exhibited much lower peak opening loads, and the damage to the vertical tapes was reduced substantially, to the point where the addition of v-tapes at the attachment points eliminated damage entirely.

The by-product of this canopy characteristic remained that the reefing at the skirt of the canopy does little to control the initial opening loads, but retains an important role in controlling the canopy skirt during deployment in order to prevent the possibility of canopy inversions, which have been experienced, for example, on the unreefed MQM-107 main canopies. A copy of a typical loads trace from flight test is shown in Figure 8.

The improved design canopies were then successfully tested and introduced on the HSFD, Rocket SST and AFSAT programs.

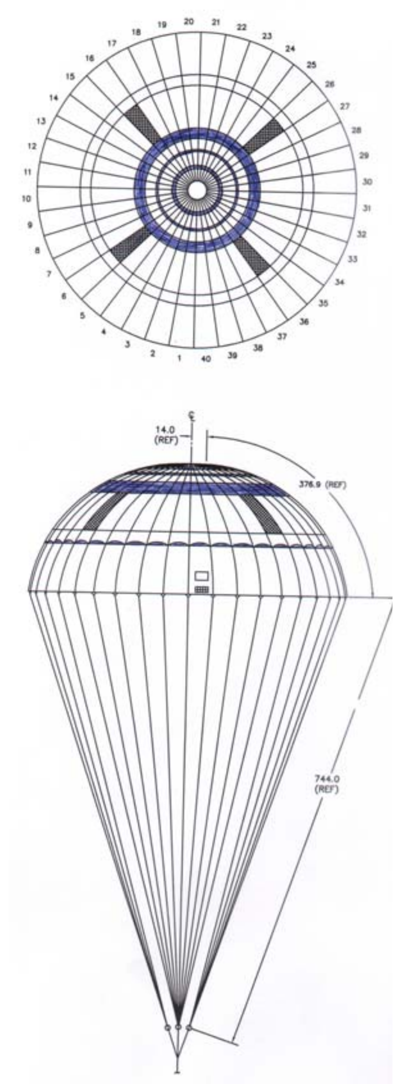

Figure 7. Revised Main Canopy Planform

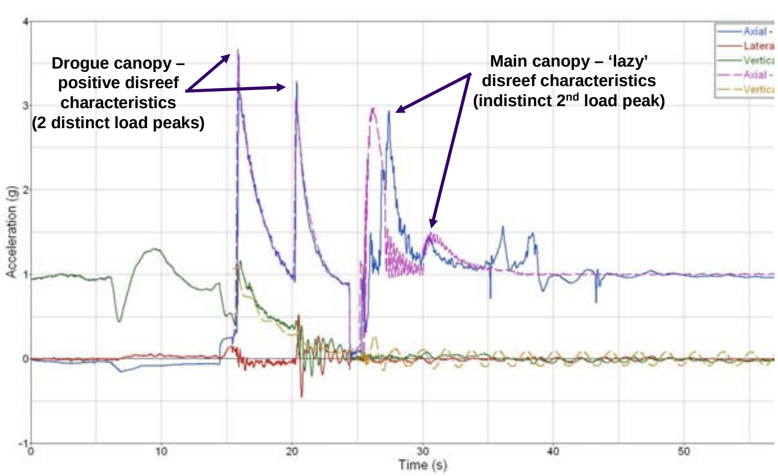

Figure 8. AFSAT Canopy Loads Trace

B. Drogue Canopy Development Tests

The testing of the drogue canopy itself was totally uneventful as far as the drogue canopy loads, drag performance and structural integrity were concerned. However, more interesting experiences were to be gained as a result of the surrogate system level testing.

The drogue tests were conducted using an Irvin Cylindrical Test Vehicle (CTV) dropped from the C-123K at Red Lake, Kingman, AZ. The testing was configured with a programmer parachute to get the CTV 'on condition'. Once 'on condition', this parachute was cut away and the drogue was then deployed. The descent under the drogue was lengthened, compared with the 8 sec AFSAT drogue ride, to maximize the time under the drogue to characterize its performance. At a pre-selected time, a 'saver' parachute was then to be deployed to slow the CTV for recovery. As might be expected, a suitable 'saver' parachute would be the 62.2 ft canopy used for the earlier main canopy deployment tests. This led to a surrogate 'system level' development test configuration.

C. System-level Development Tests

On the second of the two planned drogue canopy development tests, a structural overload test, a failure occurred with the saver parachute. Even though the saver parachute was not the item under test, this was, effectively, the AFSAT main canopy, and hence a detailed investigation into the failure was conducted.

The damage assessment revealed that some of the main canopy suspension lines had broken at both ends – both at the canopy skirt and at the riser attachment point. It appeared that simultaneous failure had occurred; if one end had failed first, then the load in the suspension line would have reduced to near zero and the line would have been expected to have remained attached at the other end. This was not the case.

The prior history of testing with the 62.2 ft canopy was raised again, however, on the prior surrogate system level test, all indications were that the canopy was performing exactly as expected, and given that the drogue ride was extended in both tests to the point where terminal velocity had been achieved, the initial conditions for saver parachute operation should have been nearly identical.

The interesting feature was the fact that the lines had broken simultaneously in two places, and this led to the suspicion that there was more to this event than a pure structural overload similar to that which had occurred with the main canopy tests. One other requirement for AFSAT that was newly implemented in these tests was retention of the drogue canopy to the main; AFSAT is required to keep all recovery system items, including the tailcone, drogue canopy and deployment bags in train so that none are lost and all can be re-used.

The structural grids of both the drogue and main canopies used high tenacity materials; Kevlar / Vectran in the drogue and all Vectran in the main canopy. Both of these materials are, by nature, 'stiff' in terms of their spring constants. It was therefore postulated that some harmonic frequency had been experienced resulting in the simultaneous failure of these suspension lines. The supposition was that the masses of the drogue parachute and main and drogue deployment bag were being reaccelerated at the same time as the inflation of the main canopy, and these two events were overlaid and had created a harmonic, or standing wave, that resulted in failure of the main canopy suspension lines.

There was no conclusive proof to this hypothesis, however, it was decided to mitigate the likelihood of this event and several options were considered. The first option was to change the stiffness of the system dramatically. This would have required changing from high tenacity materials in the main canopy structural grid to, say, Nylon. Given the weight, and more importantly available volume constraints, as by now the aircraft tail section design had

Figure 9. AFSAT CTV

been finalized, the increase in bulk with Nylon materials was untenable. The second option was to delay the reacceleration of the combined mass of the retained drogue canopy and deployment bags to a point in time after main canopy inflation was completed. This latter option was selected and a ‘kill line’ arrangement was introduced that allowed the drogue canopy and deployment bags to trail many feet behind the main canopy, with the length based on the estimated separation velocity and the main canopy deployment and inflation time. This addition was incorporated with minimum increase to the pack weight and volume.

The failed test condition was repeated and was entirely successful. The program then progressed to the ‘real’ system-level testing.

D. System-level Tests

The AFSAT procurement process was somewhat unusual in that the acquisition was truly against a Performance Based Specification. It was up to the Prime Contractor to agree amongst its subcontractors the extent and level of any subsystem or system level testing. The Government contract vehicle was to demonstrate achievement of aircraft-level Key Performance Parameters (KPPs) over a series of 12 Flight Performance Demonstration (FPD) flights, and effectively ‘qualify’ the system though in-service experience. Qualification testing, in the usual manner, was not a requirement directed by the acquisition process.

Irvin and CEi mutually agreed that the acceptance criteria for the recovery system was to achieve two successful system-level tests, and one further test where the CEi aircraft tail section and tailcone removal system were integrated with the Irvin CTV, shown in Figure 9, and the complete sequence demonstrated, Figure 10.

The last series of tests were completed relatively uneventfully – some minor lessons were learned regarding tailcone retention, but the acceptance criteria were readily demonstrated, and the AFSAT program progressed to the FPD phase.

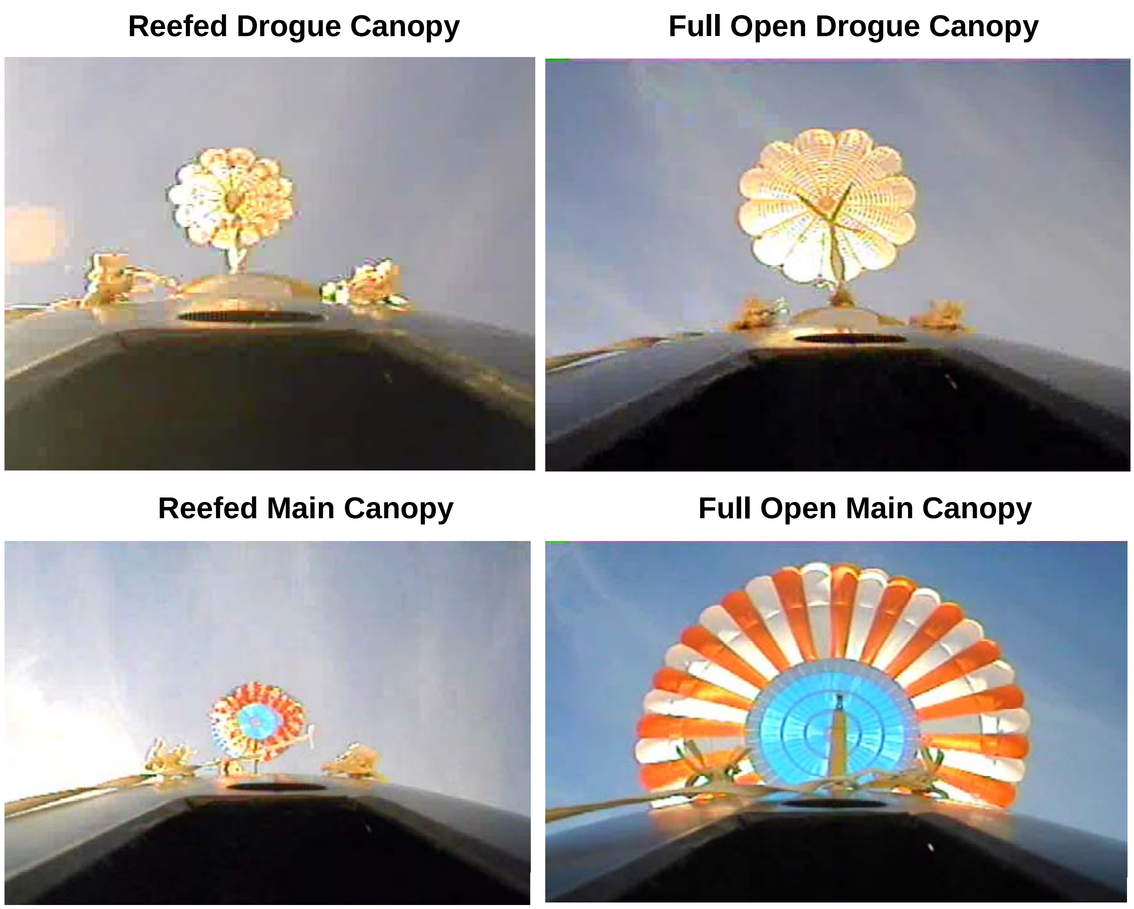

Figure 10. AFSAT System Level Tests

E. Flight Performance Demonstration Tests and Current Operations

The FPD phase was completed with aircraft flights from Tyndall Air Force Base, Florida, over a range of flight conditions, Figure 11. Over the series of flights, the AFSAT aircraft demonstrated a level of performance well in excess of all the KPPs. As is often the case, however, the initial flights of these aircraft were not without ‘learning experiences’, and the program managed to provide several unplanned parachute recoveries from corner-of-the-envelope flight conditions, including pad abort and high altitude / high speed recoveries. The AFSAT parachute recovery system performed exactly as required under all of these flight conditions and successful recoveries were achieved on every usage. Some lessons were learned, and continue to be learned, during these tests and current operations, particularly related to robustness during service usage and reliable retention of the tailcone. These are being addressed as system improvements as the AFSAT program rolls over into operational testing and entry into service.

The AFSAT parachute recovery system, shown in Figure 12, is now in rate production supporting the entry of the BQM-167A system into service.

Figure 11. AFSAT (BQM-167A)

Figure 12. AFSAT Parachute Recovery System

Glossary

AFSAT	Air Force Subscale Aerial Target
ATPS	Advanced Tactical Parachute System
CEi	Composite Engineering Inc.
CTV	Cylindrical Test Vehicle
ERS	Enhanced Recovery System
FPD	Flight Performance Demonstration
HSFD	High Speed Flight Demonstrator
KPP	Key Performance Parameters
RATO	Rocket Assisted Take-Off
SAD	Safe Arm Device
SST	Supersonic Transport