PARACHUTE TESTING FOR THE NASA X-38 CREW RETURN VEHICLE

Jenny M. Stein*
NASA Johnson Space Center, Houston, Texas 77058

NASA's X-38 program was an in-house technology demonstration program to develop a Crew Return Vehicle (CRV) for the International Space Station capable of returning seven crewmembers to Earth when the Space Shuttle was not present at the station. The program, managed out of NASA's Johnson Space Center, was started in 1995 and was cancelled in 2003. Eight flights with a prototype atmospheric vehicle were successfully flown at Edwards Air Force Base, demonstrating the feasibility of a parachute landing system for spacecraft. The intensive testing conducted by the program included testing of large ram-air parafoils. The flight test techniques, instrumentation, and simulation models developed during the parachute test program culminated in the successful demonstration of a guided parafoil system to land a 25,000 lb spacecraft. The test program utilized parafoils of sizes ranging from 750 ft^2 to 7500 ft^2. The guidance, navigation, and control system (GN&C) consisted of winches, laser or radar altimeter, global positioning system (GPS), magnetic compass, barometric altimeter, flight computer, and modems for uplink commands and downlink data. The winches were used to steer the parafoil and to perform the dynamic flare maneuver for a soft landing. The laser or radar altimeter was used to initiate the flare. In the event of a GPS failure, the software navigated by dead reckoning using the compass and barometric altimeter data. The GN&C test beds included platforms dropped from cargo aircraft, atmospheric vehicles released from a B-52, and a Buckeye powered parachute. This paper will describe the test program and significant results.

ACRONYMS, ABBREVIATIONS, SYMBOLS

AGL	=	Above Ground Level
CDS	=	Cargo Delivery System
CRV	=	Crew Return Vehicle
DSS	=	Decelerator System Simulation
EAFB	=	Edwards Air Force Base
EMC	=	Energy Management System
ESA	=	European Space Agency
ft	=	foot
ft^2	=	square foot
GN&C	=	Guidance, Navigation, and Control
GPS	=	Global Positioning System
MSL	=	Mean Sea Level

* Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for first author.

NSI = NASA Standard Initiator
PDS = Parafoil Dynamics Simulator

INTRODUCTION

NASA established the X-38 program in 1995 to develop and fly a prototype for a Crew Return Vehicle (CRV) to replace the Soyuz spacecraft currently used on the International Space Station[1]. Although the program was cancelled in 2003, the X-38 program successfully demonstrated the feasibility of the prototype configuration. A large part of the success can be attributed to the application of the program's philosophy of "Build a little, test a little, fix a little".

A lifting body shape was selected for the CRV due to the lifting body's large cross range capability for re-entry from Earth orbit. A lifting body's landing speed is 250 knots, requiring long runways and intensive pilot training. To reduce the CRV's horizontal landing speeds, the program designed the primary landing system around a parafoil capable of performing a dynamic flare. The parafoil offered several advantages over a cluster of large round parachutes to land the vehicle. The parafoil could be autonomously or manually steered to a pre-determined landing target, turned into the wind, flared, and landed using a guidance, navigation and control system (GN&C). Another advantage of using a parafoil landing system was the increased assurance of landing with the vehicle nose in-line with the system's velocity vector, which was critical for the design of the vehicle structure and crew couches to handle the landing impact loads.

The development of the parafoil system turned out to be a much greater challenge than was initially anticipated. The parafoil size required to land such a heavy vehicle was 7,500 ft^2. This large size was well beyond the parafoil technology at that time. One of the biggest challenges with such a large parafoil was to achieve a repeatable, low dynamic, on-heading opening and inflation of the parafoil. A significant portion of the test program was concentrated upon that challenge, and by the end of the X-38 program, that challenge had been met.

Other challenges that the program encountered were those associated with using a parachute landing system on a human-rated spacecraft. A parachute landing system has not been the primary means to land a spacecraft since Apollo. As a result, during the X-38 test program several interesting and challenging issues were identified by management and by astronauts, which required increased testing to solve. Two of these issues were aesthetics of deployment and ride quality.

The aesthetics of deployment was basically an individual's perception of what a parachute's deployment sequence looked like from the ground and what kind of ride a crew would experience. A visual observation is very subjective and varies between individuals and therefore is difficult to address. The Space Shuttle Orbiter, for example, is a lifting body that approaches from space on a relatively smooth flight profile. On the other hand, a parachute deployment is rather dynamic with motion not only of the inflating parachute, but with motion induced on the test article from the parachute dynamics. Acceleronometer data was used to evaluate the vehicle rates during deployment. Some rates were unacceptable and had to be reduced; other rates were within the tight limits for ill or de-conditioned astronauts, but the visual observations from the ground overwhelmed the assessment, thus requiring that those rates be reduced as well. An important finding of the X-38 program is that the aesthetics of deployment and the ride quality for a crew must be at the highest quality possible, which will be a challenge for any parachute landing system.

To tackle these and other challenges, NASA conducted an intensive test program, developed new simulation models, and incorporated more instrumentation into the tests than had been done to date on parachutes. This paper will describe the parachute system, including the parafoil Guidance, Navigation, and Control (PGNC) system, the test program, instrumentation, and simulation models used in the X-38 program.

X-38 PROGRAM OVERVIEW

Between 1995 and 2003, NASA's X-38 program developed a prototype of the CRV to replace the Soyuz to return the International Space Station crew to Earth if the Space Shuttle was unavailable. The CRV was to be carried to orbit in the Space Shuttle Orbiter's payload bay, released, as shown in figure 1, and attached to the International Space Station.

The lifting body shape initially selected for the CRV was the Air Force's X-24A because the aerodynamic database for this shape was well documented. Two fiberglass prototype vehicles, designated V-131 and V-132, were constructed for use in flight-testing at Edwards Air Force Base (EAFB). These vehicles had the CRV's outer mold line and many of the spacecraft flight systems, including the vehicle GN&C software and control surfaces, power, and life support systems. Each vehicle weighed 15,000 lbs and would accommodate 4 crewmembers. A 5,500 ft^2 parafoil and a 60-ft diameter drogue parachute were designed and extensively tested with these test vehicles. For a flight test, one of the vehicles was attached to the B-52 pylon, taken to the designated release coordinates, and released, as shown in figure 2. Five successful flight tests were conducted: two using V-131 and three using V-132.

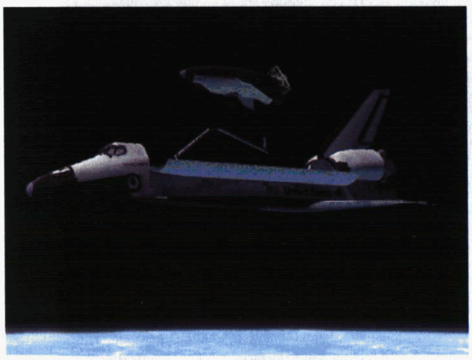


Figure 1. CRV being deployed into space by Shuttle

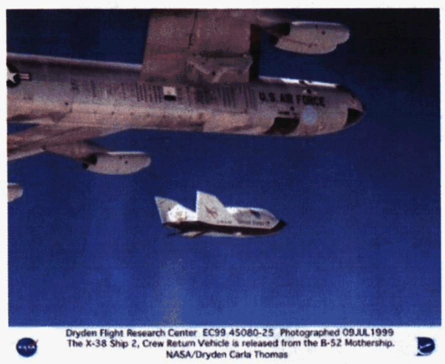
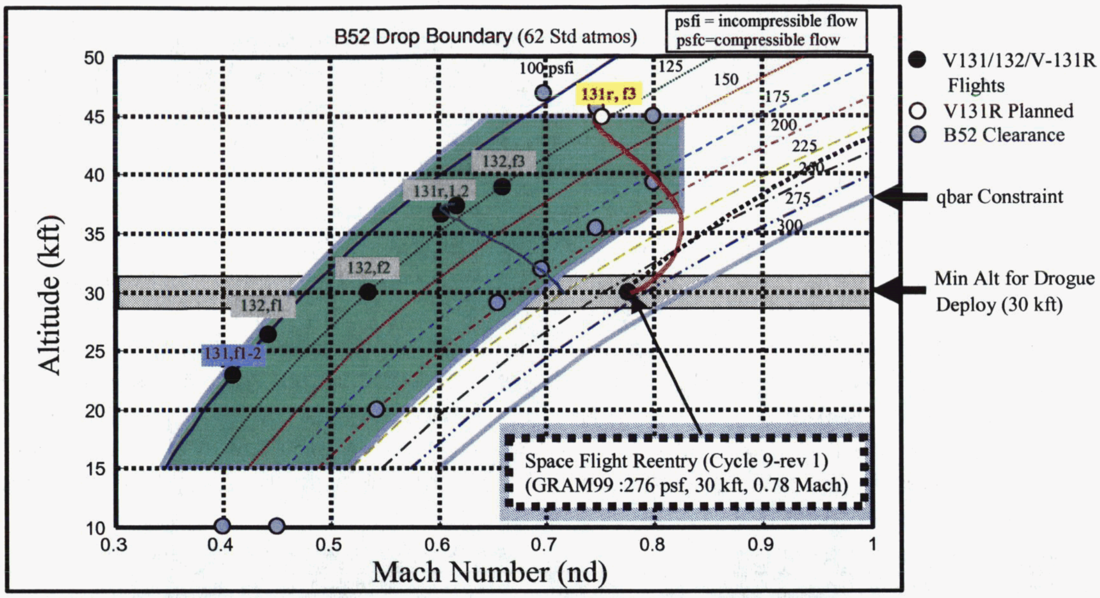


Figure 2. V-132 released from B-52 for flight test.

Then the vehicle requirements were changed to accommodate 7 crewmembers, resulting in the vehicle weight increasing to 25,000 lb. The outer mold line was also adjusted to provide increased crew volume, based upon design work done by the European Space Agency (ESA) who was one of the CRV's international partners. This weight increase led to the design of a 7500 ft^2 parafoil and an 80-ft diameter drogue parachute. V-131 was modified to incorporate as many features of the larger vehicle design that could reasonably be added and was re-designated as V131R, which is shown in figure 3.

Figure 3. V-131R flight test.

However, due to limitations of its composite structure, V131R could only be ballasted to 18,000 lbs. Three successful flight tests were conducted using V-131R. Figure 4 shows the release conditions for the flights. On the eighth and final flight of the program, V-131R was released from the B-52, intercepted the trajectory that the CRV would have flown from space, shown as the dotted line in the figure, and deployed the drogue at the target dynamic pressure.



V131r Potential Drop Conditions

	Drop Alt (kft)	Mach	Qbar (psfi)
1.	36.5	0.60	117
2.	37.5	0.62	117
3.	**45.0**	**0.75**	**122**

→

V131r Drogue Deploy Conditions

Mach	Qbar (psfi)	Flight Duration (secs)
0.70	217	24
0.72	226	29
0.78	**267**	**47.5**

Figure 4. V-130 series drop conditions.

The final phase of the X-38 program was to fly an unmanned spaceflight test using a vehicle, designated as V-201. This vehicle is shown in figure 5 and was being outfitted with all of the CRV flight systems and an instrumented mannequin. The 25,000 lb vehicle was to be carried to orbit in the Space Shuttle Orbiter payload bay, released, and then flown autonomously to a landing site in Woomera, Australia. The build up of V-201 was done at Johnson Space Center and was about 75% complete at the time the program was cancelled.

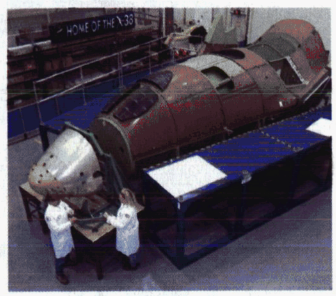


Figure 5. V-201.

In preparation for the flight-testing at EAFB, the X-38 program conducted an extensive parachute development and test program, as summarized table 1. Simulation models for parachute systems were developed and were important design tools. However, due to the random nature of parachute deployments and inflation, testing was still the primary tool for demonstrating parachute deployment, inflation, and performance. Analytical methods cannot account for the physical details of how a parachute is packed and deployed from a deployment bag. Testing was used in all phases of the development of the parachute system. Testing of components led to testing of subassemblies. Parachutes were then tested individually, culminating into full-scale parachute system testing. Creative techniques were identified and used to test as much of the components of a parachute system as possible prior to the more expensive full-scale parachute system, increasing the success of the final testing.

Included in Table 1 are DTV tests conducted on a concept for a supersonic parachute, which was being evaluated for the CRV. If the CRV were to lose attitude control during the transonic regime, there was a vehicle controllability issue. Deployment of a supersonic-capable parachute was one solution for this controllability issue. A 16 ft parachute was built and tested but was never incorporated into the parachute sequence.

Test Article	Drop Aircraft	Parfoil (ft^2)	Drogue (ft diameter)	Supersonic (ft diameter)	Backup Parachute System	Material Test Chute (ft diameter)	Number of Tests
Small tub	Huey	750	N/A				300+
Platform	C-130, C-141, or C-17	3,600	60				5
		5,500	60				15
		7,350	60				6
		7,500	80				7
		7,500	100				3
		N/A	N/A		26 ft drogue & 124 ft main		3
		N/A	80				4
DTV	CH-47	N/A	60				1
			63				5
			80				4
			100				2
DTV	UH-1	N/A		16			8
						26.5	2
V-131	B-52	5,500	60				2
V-132	B-52	5,500	60				3
V-131R	B-52	7,500	80				3
Buckeye	N/A	500 ft^2 not of X-38 design	N/A				Series of 30 PGNC flights

Table 1. X-38 parachute drop test history.

The parafoil drop test program included testing of subscale and full-scale parafoils. The subscale parafoil was a geometric model of the full-scale design and had a wing area of 750 ft^2. Tow tests behind a truck, shown in figure 6, were conducted at Yuma Proving Ground, JSC, and Texas A&M University to evaluate parafoil inflation and aerodynamic characteristics, especially line length ratio and rigging angle[2]. As the tow tests were conducted during the X-38 program, the instrumentation improved. A winch and motor package was used to set the flaps. Sensors included an anemometer, air data probe, control stroke potentiometers, riser angle potentiometers, and suspension line loads cells. A data acquisition system recorded the data.

Figure 6. Truck tow test of 750 sq ft parafoil

Another important test technique was the subscale parafoil drop test. Over 300 drop tests were conducted by dropping a 750 ft^2 subscale parafoil from a UH-1 helicopter, as shown in figure 7. These drop tests were a very cost effective test technique for parafoil development. Many of the drop tests were done using only the first stage of the parafoil because the deployment was the biggest challenge of the parafoil design and development. That had the advantage of not needing to add the reefing cutters for the other stages. Therefore, the short turnaround to recover the parafoil, repack the parafoil, rig the parafoil to the load, and conduct a subsequent drop allowed the team to perform five to eight drops a day. Two parafoils were used which also increased the number of drops in a day.

Figure 7. Subscale parafoil test article being loaded into drop helicopter.

The payload weight used for the drop tests was selected using mass ratio scaling. As a result, the deployment dynamics and parafoil flight qualities in the subscale parafoil drop tests were similar to the full-scale parafoil drop tests. The flight qualities of particular interest included rebound, inflation time, inflation load, parafoil surge, roll stability, brake release dynamics, trim angle of attack, and disreefing. The capability to test design features in a subscale parafoil and then scale those changes up to a full-scale parafoil proved to be a major factor in the successful development of the parafoil.

The subscale drop configuration consisted of a rectangular metal box ballasted to 930 lb. The parafoil and a 13.5 ft cruciform drogue were rigged to the load. The load was secured to a rail installed inside of the helicopter, as shown in figure 7. A static line was attached to the drogue. The drop altitude ranged from 1,500 ft to 2,500 ft AGL depending upon the parafoil configuration to be tested. The lower altitude was used for first stage only parafoil tests and the higher altitude for the full open parafoil tests. When the helicopter reached the drop altitude, a crewmember on board manually cut the webbing securing the load to the rail and then pushed the load out of the door. As the load fell away from the helicopter, the static line deployed the drogue and armed the drogue's 8 second cutter. After the time delay expired, the cutter fired, releasing the drogue and thus deploying the parafoil. The instrumentation on the parafoil normally consisted of a load cell on the parafoil riser to capture the total load and a load cell on the leading edge of the parafoil lower surface to measure the parafoil's spreading forces. Ground-to-air video was taken for each drop. Tracking data was obtained for the drops when the parafoil was disreefed to full open.

To test full-scale parafoils, the program conducted 42 platform airdrops from cargo aircraft, including the C-130, C-141, and C-17, providing the primary drop test technique to develop and demonstrate the full-scale parachute systems. Details of the test article configurations, design development, problems, changes, and results are described in references 1and 3. A typical parafoil platform configuration is shown in figure 8. The platform was suspended from a crane so that a compass calibration could be performed. The parafoil pack is rigged into the grey metal box, which represents the vehicle compartment. The drogue pack is the white bag to the right of the parafoil box. The instrumentation was mounted in the blue test tub. The air data probe was housed in the grey metal housing on the platform behind the engineers. After the platform was extracted from the airplane, a timing circuit was activated for deployment of the air data probe, which was extended on a boom in attempt to place the boom is cleaner air. Figure 9 shows the 7,500 ft^2 parafoil in flight.

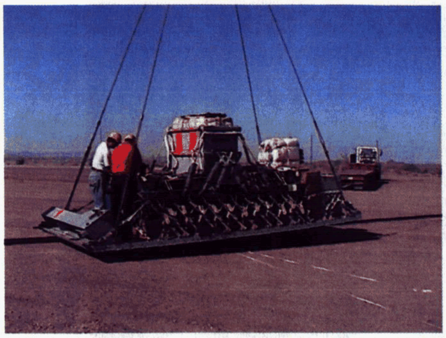


Figure 8. Parachute platform rigged for drop test.

Figure 9. 7,500 sq ft parafoil.

Another unique type of platform test article was built to demonstrate parachute extraction from V-131's parachute compartments. This test article was referred to as the doghouse and is shown in figure 10. On top of a standard airdrop test tub, the program built a structure to simulate the parachute compartments and as much of the outer mold line as possible, given the ramp height limitation of a C-130. Two drop tests were conducted to demonstrate the extraction of the parafoil from the V-131 compartment; on the second drop test, the mortar was installed and fired to deploy the pilot parachute. The third and final drop test of the doghouse was to demonstrate the backup parachute system prior to flying the first flight of V-131. The parafoil was deployed and then cut away, as it would to prepare for backup parachute deployment. Then the backup parachute mortar was fired, deploying the pilot parachute and drogue. After the appropriate time delay, the drogue should have been released.

Figure 10. Doghouse test article under a 7,350 sq ft parafoil.

However, due to shorts in the pyro system, there was insufficient power to fire the drogue strap cutters. Instead of landing under the 124 ft main, the 20,000 lb doghouse landed under the 26 ft drogue, resulting in the loss of the test article. The test, however, successfully demonstrated the cut away of the parafoil and deployment of the backup drogue, which was sufficient to commence V-131 drop tests. The backup parachute system was considered part of the vehicle's flight termination system. The range had agreed to allow the backup parachute system be initiated in the event of a parafoil system failure, in order to save the vehicle. If the backup system failed or if the vehicle was drifting off range, the range safety officer would fire the second leg of the flight termination system, which was a small 7 ft diameter parachute referred to as the offset parachute. This parachute was mounted on the rear of the vehicle in the starboard lower corner and was intended to kill vehicle lift and limit the vehicle's range during its descent. Fortunately, neither the backup parachute system nor the offset parachute was used on any of the eight V-130 series flight tests.

Another test technique was developed to suspend a bomb-like test article, called a Drogue Test Article (DTV), below a helicopter and release the DTV from the designated altitude. This technique was not only a more cost effective technique to test round parachutes but it also provided the program's only technique to deploy the drogue parachute or to test candidate parachute materials at the high dynamic pressure needed for the atmospheric vehicle drops. There were three sizes of DTVs. The small (1,600 lb) and medium (2,000 to 5,000 lb range) DTVs were suspended under a UH-1 helicopter, as shown in figure 11, then dropped over the drop zone target to test small parachutes. The large DTV was needed to test the large drogue parachutes and could be ballasted from 10,000 to 15,000 lbs. Figure 12 shows the large DTV being prepared to be dropped by the CH-47. The parachute to be tested was packed in its deployment bag and rigged into a box on the DTV. The DTV was attached to a bridle the drop helicopter could pick up the DTV. The helicopter then climbed to drop altitude and position and released the DTV. A static deployment line attached to the helicopter deployed the pilot to start the sequence. The drop altitude was driven by the weight of the test article. To reach a drogue deployment dynamic pressure of 350 psf on the 80 ft drogue, for example, the DTV weight was limited to 10,000 lb because the CH-47 had to be able to climb to 14,000 ft MSL.

Figure 11. Medium DTV positioned on ground by Huey in preparation for drop test (DTV-10).

Figure 12. CH-47 climbing to drop altitude with large DTV.

The Buckeye powered parachute test vehicle, shown in figure 13, provided an excellent test bed for the PGNC[4]. The Buckeye was modified by Southwest Research Institute, which is located in San Antonio, Texas, to enable the vehicle to fly autonomously or via remote commands from the ground. For the flight test operations, the Buckeye was flown to altitude, the engine was turned off, and the X-38 GN&C was activated. The GN&C then flew the gliding Buckeye autonomously based upon the information loaded into the software for that specific test flight. When a minimum altitude was reached, the ground pilot restarted the engine via remote commands and flew the Buckeye back up to altitude to begin another GN&C test flight case. Figure 13 shows the Buckeye in flight under a the Buckeye's standard 500 ft^2 parafoil.

Figure 13. Buckeye powered parachute.

Except for the winches, which are canopy specific, all of the GN&C software and hardware used on the platform, along with most used on the atmospheric vehicle, were tested using the

Buckeye. The Buckeye provided a cost-effective test bed to test hardware and software changes before incorporating them into the more expensive drop test configurations. Flight testing was initially conducted at Yuma Proving Ground and then moved to Texas A&M University's Riverside Campus.

X-38 PARACHUTE SYSTEM DESCRIPTION

The X-38 parachute systems consisted of a primary parachute system and a backup parachute system. In the event of a failure in the primary parachute system, the primary system would have been cut away and the backup parachute system deployed.

Parachute Deployment Sequence

The final primary parachute system had a mortar-deployed, 9-foot diameter ribbon pilot parachute, a 100-foot quarter-spherical ribbon drogue parachute, and a 7,500 ft^2 parafoil. The backup parachute had the same type of pilot parachute as the primary system, a 26-foot ribbon drogue parachute, and a 124-foot hybrid ribbon/solid parachute. The following figure illustrates sequence of events for each system.

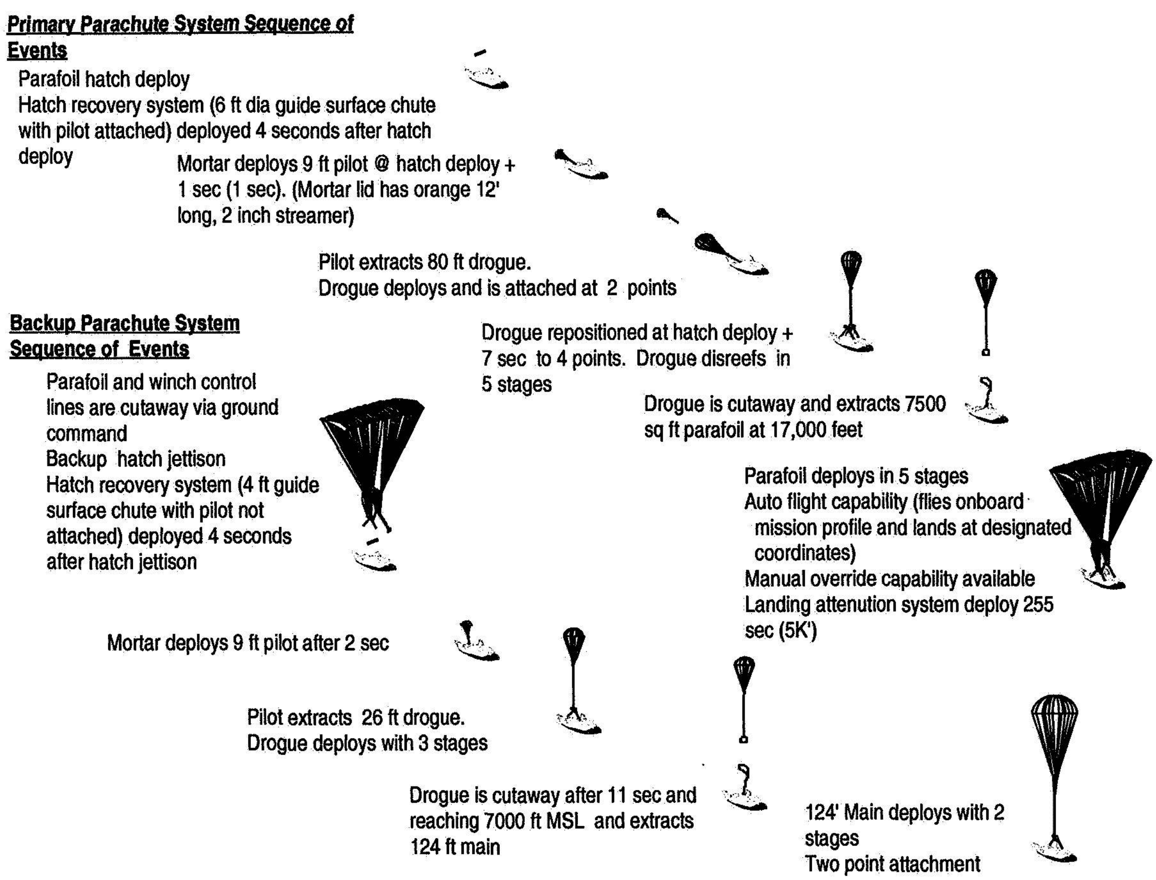


Figure 14. Parachute deployment sequence.

A hatch covered the parafoil compartment. At the hatch deploy time, pyrotechnic pin pullers were activated, releasing the springs held in tension, thus pushing the hatch forward edge above the mold line. Once in the airstream, the hatch quickly cleared the vehicle. A parachute, discussed later in this paper, was installed on the hatch to ensure that the hatch would land on the range and within a known footprint.

Four seconds after the jettison of the hatch, the mortar was fired to deploy the 9-foot pilot parachute. The mortar was located in the aft section of the vehicle and fired in the opposite direction of the vehicle's velocity vector at an altitude between 23,000 and 30,000 feet MSL, depending upon the flight test's altitude. The mortar propelled the pilot parachute into the airflow behind the vehicle where the parachute inflated. Because the parachute was attached to the drogue pack, the pilot parachute extracted the 100-foot drogue parachute out of its compartment and then out of its deployment bag.

The drogue stabilized and decelerated the vehicle. Initially the drogue is connected to the vehicle at two attach points on the vehicle's aft base. The drogue's peak loads were kept under 3 g's during deployment by opening the drogue in 5 stages. Parachutes are opened in stages because trying to inflate a parachute all at once would over load the parachute and also transmit too much load back into the vehicle at the parachute attachment points. Each stage opens the skirt to a larger diameter. A textile cord called a reefing line was used to limit the opening of the skirt for a stage. A reefing line was routed through reefing rings sewn to the skirt. The disreefing of each stage was accomplished using redundant reefing pyrotechnic cutters, which were mechanically actuated. Each cutter had a textile lanyard tied to its actuation pin. The other end of the lanyard was attached to a suspension line, with enough slack to prevent premature actuation during the parachute packing process. Each cutter's lanyard was attached to a different suspension line. At parachute line stretch, the lanyards were pulled for all stages, activating the delay charge in each cutter. The delay charges for each stage were selected to obtain the desired timing sequence. At the end of the delay, the main propellant charge was ignited. The pressure generated moved the blade inside the cutter, cutting the reefing line and allowing the skirt to open to the next stage. Orientation of each cutter was important to achieve a straight pull on the lanyard.

As the drogue slowed the vehicle, a reposition event was used to transition from the two point attach to the four point attach, in preparation for parafoil deployment. The four point attachment fittings were on the top surface of the vehicle. When the vehicle reached 15,000 to 20,000 ft MSL, depending upon the specific flight test trajectory, the drogue was released from the vehicle by severing the slings with pyrotechnic strap cutters. The strap cutters had redundant NASA Standard Initiators (NSIs). Parachute drop testing used electrical current to fire the NSIs. The atmospheric vehicle used lasers to fire the NSIs, which was thought to be a better solution for a space application. Another change for the atmospheric vehicle configuration was that NASA provided the strap cutter hardware, which had improved body construction and propellant mixture.

A deployment line was attached the parafoil's deployment bag to one of the drogue slings so that when the drogue was cut away, the drogue extracted the parafoil from its vehicle compartment. At line stretch, the parafoil was extracted out of its bag. The drogue remained attached to the parafoil via an energy modulator that was attached between the deployment sleeve and the upper surface of the parafoil's canopy. The energy modulator maintained tension on the parafoil suspension system during the first stage inflation, resulting in a quick, repeatable spreading of the canopy into first stage. After stroking, the energy modulator separated with one end of the modulator remaining attached to the bag and the other end to the parafoil canopy. Unintentionally, the modulator remaining attached to the canopy served as a flow indicator in a way like tuffs do on an airplane or in a wind tunnel, providing insight into the parafoil flight characteristics during inflation.

The parafoil was opened in 5 stages. After the third stage, the confluence fitting was separated, and after 5th stage (full open) the deployment brakes were released. All parachute staging, parafoil deployment bag mouth opening, confluence separation, and deployment brakes release were accomplished using the mechanically initiated pyrotechnic cutters. The parafoil was attached to the vehicle at the four attachment fittings on the top surface of the vehicle. The parafoil control surfaces were the outer 25% of the trailing edge, leaving the middle 50% un-deflected. Each control surface had a control line, which was attached to a winch for steering control. GN&C software autonomously flew the test article to the target, turned into the wind, and performed a flared landing. The flare was initiated based upon altitude obtained from a ground relative laser or radar altimeter. Manual override was available from the ground control station to steer the parafoil from a ground station.

Hatch Parachute

There was a hatch over the parafoil compartment and another hatch over the backup parachute compartment. For a normal flight test, only the parafoil hatch would have been jettisoned. Once a hatch is jettisoned, it becomes a piece of debris that not only must land on the range but it must not become a hazard to the chase aircraft or to the recovery team on the ground. Subscale testing, using plywood models, showed that a hatch in free fall could generate sufficient lift to "fly", resulting in increased uncertainty in the landing footprint. The solution to "kill" the lift was to install a parachute on the hatch. Additional testing demonstrated that the addition of a ballast plate in the corner of the hatch directly opposite of the parachute attachment point reduced hatch oscillations under the parachute and increased the sink rate.

The parafoil compartment hatch was 63 inches by 70 inches and weighed 98 lbs. A 20 lb ballast plate and a 6 foot ribless guide surface parachute, which had about a 20 ft^2 drag area, were installed on the parafoil hatch. The backup parachute compartment hatch was 55 inches by 44 inches and weighed 46 lbs. A 10 lb ballast plate and a 4 foot ribless guide surface parachute, which had about a 10 ft^2 drag area, were installed on the backup parachute hatch. Each parachute had a 50-foot riser made of 4 plies of 6,000 lb Kevlar webbing. The riser was attached to a Y bridle made of 4 plies of 6,000 lb Kevlar webbing. Each leg of the bridle was about 1 foot long. The parachute pack, as shown in figure 15, was mounted on the inside surface of the hatch. When the hatch was jettisoned from the vehicle, textile lanyards tied to the vehicle would pull the actuation pins off of the redundant mechanically actuated pyrotechnic cutters, each having a 4 second time delay, that were used to close the parachute pack. After the 4 second time delay expired, the cutters fired and opened the parachute

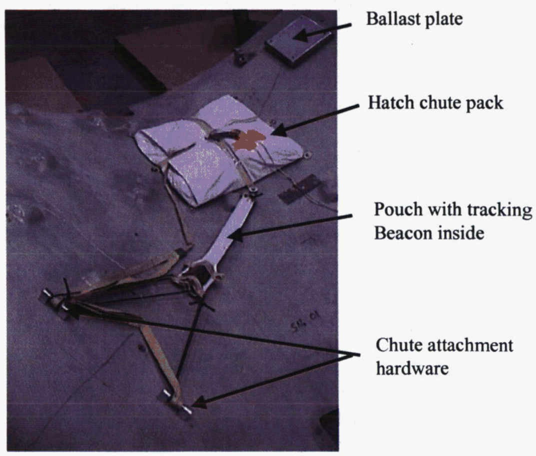


Figure 15. Parafoil hatch parachute rigging.

pack, releasing the spring loaded vane pilot parachute into the freestream and thus deploying the hatch parachute. A side benefit of using the hatch parachute was that the hatch was recovered intact and reused for the next flight test.

A drop test was conducted to demonstrate the hatch parachute performance, confirm the drag area, and to obtain the sink rate of the hatch under the parachute. This data was needed for the range safety tool to predict the footprint of all released components to verify that all components would remain on the range given the wind data for that drop day. The drop test was accomplished by rigging an actual hatch to a standard 1,500 lb Cargo Delivery System (CDS) bundle, as shown in figure 16, used by aircrews to practice airdrops. A static line was connected to the CDS bundle to deploy the standard 64 ft cargo parachute to recover the CDS bundle. The deployment of the cargo parachute armed 4 second reefing cutter which released the hatch from the CDS bundle. After release from the CDS bundle, the hatch parachute 10 second reefing cutter was armed. After 10 seconds, the cutter fired, releasing a spring loaded vane pilot chute which in turn deployed the 6 ft ribless guide surface parachute. The test was successful.

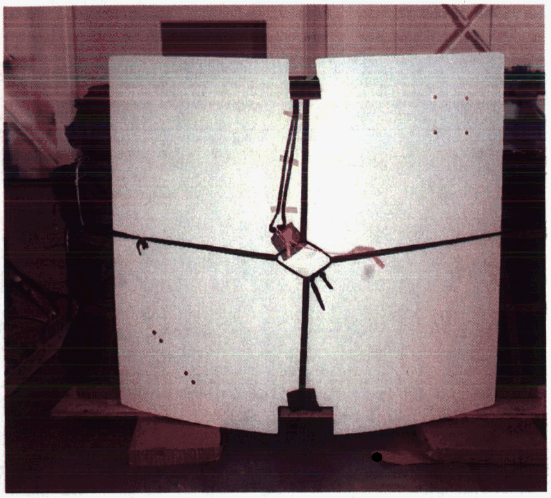


Figure 16. Hatch chute drop test.

The hatch parachutes were used successfully on all eight vehicle flight tests. Minor damage occurred on the first drop of V132 drop due to twist up of the parachute riser during descent. The twist was significant enough to reduce the parachute's drag area, resulting in a faster descent rate and thus a harder landing. The problem was eliminated by installing a metal swivel at the end of the riser connection to the parachute suspension lines to allow the parachute to rotate with out twisting the riser.

Pilot Parachute

The pilot parachute was a 9-foot diameter nylon ribbon pilot parachute from the Orbiter drag parachute system. The parachute had a geometric porosity of 19.3%, and a total porosity of 24.9%. The X-38 program incorporated changes in some of the parachute components to meet the higher X-38 deployment dynamic pressure requirements for both the primary and backup parachute systems. The design dynamic pressures for the primary and backup pilot parachutes were 260+/- 35 psf and 430 psf, respectively. Changes in the Orbiter pilot were incorporated to meet the high dynamic pressures. Nylon suspension lines, radials, and vent lines were replaced with 4,000 lb Kevlar material, and the nylon riser was replaced with 6 plies of 6,000 lb Kevlar webbing. A 6,000 lb separable link was installed at the confluence point joining the riser with the suspension lines. The changes were verified by conducting drop tests. The color of the parachute was changed from white to orange so that the parachute would be easier to be seen by the chase aircraft crew.

The pilot parachute was expelled from the vehicle using an unmodified mortar developed and used in the Space Shuttle Orbiter's landing drag parachute system. By selecting a space-qualified mortar system, the X-38 program did not have to develop a new mortar. The X-38 program did conduct one ground test due to the changes made in the parachute, which resulted in the packed weight decreasing from 12.5 lbs to 12 lbs. As expected, the slight change in weight did not have an adverse effect on the mortar's performance. A 12 foot long orange streamer made of 460 lb nylon ribbon was also riveted to the primary mortar's lid. There was concern that the lid could auto-rotate in an erractic, spiraling trajectory, resulting in a large footprint and a potential hazard for the chase aircraft. The configuration and sink rate information needed for the footprint predictor tool was obtained by conducting drop tests of lids with and without streamers. The tests were performed from a UH-1 helicopter at altitudes ranging from 1000 to 3000 ft AGL.

The pilot parachute was attached to the drogue parachute's deployment bag. The function of the pilot parachute was to extract the drogue from the vehicle compartment and then from its deployment bag. To perform this function, the pilot had to have sufficient drag area to provide the required extraction forces. The full open drag area of the 9-foot parachute was 43 ft^2. This drag area was flown on the first three atmospheric vehicle drop tests to deploy the 60 ft drogue. Post flight inspection of the drogue on these flights revealed significant damage in the drogue's vent area. Steps were taken to strengthen the vent area of the drogue. The crown of the parachute was replaced with stronger material. The diameter was also increased to 63 ft to reduce the parafoil deployment dynamic pressure. Five DTV tests were performed on the 63 ft drogue to verify the configuration. Eventually, the root cause of the problem was identified - the pilot parachute had too much drag area, resulting in the pilot parachute pulling the drogue too quickly out of its bag and thus causing frictional burning of the canopy material. Frictional burns weakened the canopy material such that the material tore when the peak loads were reached during parachute inflation. Fortunately, the damage was not severe enough to cause drogue failure.

Therefore, drag area of the pilot parachute had to be reduced. Calculations indicated that the drag area needed to be reduced from 35 ft^2 to 7.8 ft^2. The reduction was achieved by shortening the over-inflation line located in the parachute skirt to serve as a permanent reefing line. This new configuration was successfully flown on the next two atmospheric flights with no subsequent damage to the drogue. When the vehicle weight was increased, the drogue parachute size was increased first to 80 feet and then to the final configuration of 100 feet. Adjustment of the pilot parachute's drag area was required for the larger drogues. The question was how to verify any adjustment with drop testing.

First, four low altitude, low speed reefing tests were performed in March 1999 from a small helicopter to obtain a relationship of drag area versus reefing line length. A 60-lb ballast was attached to the pilot parachute. The two highest drag areas (43 and 12 ft^2) were dropped from 1,050 ft AGL, and the two lowest drag areas (7 and 4 ft^2) were dropped from 2,050 ft AGL to provide more descent time to evaluate the drag area. A drag area of 12 ft^2 was selected for test on the 80 ft drogue.

Next, the X-38 program developed a test technique using the DTV to conduct tests at the flight dynamic pressures for pilot and drogue parachute deployment. For the first test (March 10, 2000), the pilot parachute's drag area was configured for 12 ft^2, and the test article was ballasted to 10,165 lbs. When the test article was released from the helicopter at 15,200 ft MSL, the pilot parachute was statically deployed. The pilot extracted the drogue out of the test article and then out of its deployment bag. However, there was some drogue suspension line sail, indicating insufficient pilot parachute drag area to maintain tension in the system. The drogue deployment dynamic pressure achieved on the drop was 330 psf, which exceeded the design range for the flight vehicle of 260 +/- 35 psf in order to demonstrate margin. The drop test was repeated on April 23, 2000 with the pilot parachute's drag area increased to 19 ft^2. Drogue deployment occurred at 318 psf with no line sail. The pilot parachute, configured with 19 square feet of drag area, successfully deployed the drogue on the final three atmospheric vehicle drops.

Drogue Parachute

A drogue parachute has several functions: decelerate and stabilize the vehicle in preparation for main parachute deployment, extract the main from the vehicle compartment, and extract the main from its deployment bag. In the X-38 program, the main parachute was a parafoil for the primary system and a round parachute for the backup system. The size of the drogue was driven by the weight of the test article and required deployment conditions for the main parachute. As shown in Table 1, four sizes of drogue parachutes were used in the X-38 program.

The drogue for the 25,000 lb CRV was changed from a ringslot to a ribbon design, which was a more appropriated design for high dynamic pressure deployments, and was sized initially at 80 ft to decelerate the vehicle to the required parachute deployment conditions[6]. To further reduce the dynamic pressure for parafoil deployment, the drogue size was increased to 100 ft[7]. The testing performed on the drogues is summarized in Table 1. A new drogue parachute was first drop tested at low dynamic pressure on a platform to verify the design, drag area, and reefing ratios and then drop tested using the large DTV to verify performance at the design dynamic pressure before clearing the drogue for use on platform drops and vehicle flight tests. The AIAA references for the drogue parachutes provide details of the drogue design and testing.

Wind tunnel testing was conducted on the vehicle to define the vehicle's wake environment, which was needed to select the drogue trailing distance. An adverse wake environment affects drogue parachute inflation, especially in the first stage. Even with the drogue positioned at the optimal position in the wake, the shape of the drogue's first stage was distorted, however, the drogue did properly inflate and provide the required drag area.

The X-38 program did not anticipate the type of dynamics that occurred on the atmospheric vehicle flight tests. There was an interaction between the parachutes and the vehicle, which did not occur on the platform drops, resulting in adverse vehicle dynamics. The drogue was deployed to decelerate and slow the vehicle and was attached at two fittings on the aft face of the vehicle. The drogue had to be repositioned a location above the vehicle in preparation to deploy the parafoil for landing. That transition from the two aft attach points to the four attach points on top of the vehicle resulted in unacceptable pitch dynamics, because the forward fittings would load up first and pull the vehicle nose up, resulting in pitch dynamics until all four slings were equally loaded. The rates did exceed the crew limits. Model simulations were used to determine the proper time to execute that reposition event with the least amount of dynamics, however, the pitch rate was still too high.

The reposition dynamics were reduced by the addition of an energy modulator, whose strip out load was initially sized by model simulations, to the drogue slings. The energy modulator had to be built with tighter tolerances on the stitching to achieve the desired strip out load.

Two full-scale platform drop tests were conducted to refine the energy modulator design and rigging. The final two V-131R flights were flown with the energy modulator. This technique was successfully demonstrated although additional refinement was still needed to increase its effectiveness. The energy modulator configuration is shown in figure 17. To verify the rigging, the slings were suspended above V-131R. The energy modulator was made out of yellow Kevlar webbing and is located at the top of the picture. An energy modulator is constructed by taking webbing and forming bights, which are sewn together.

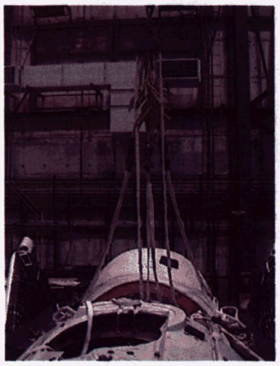


Figure 17. Reposition energy modulator (P3D8).

The simulations also showed that adding an additional reposition event would further reduce the pitch dynamics. Therefore, the sequence was changed. The first reposition event, repo 1, repositioned the drogue from the 2 point to the 4 point attach but with the aft slings sized to position the vehicle with a 70 degree hang angle. Then the second event, repo 2, cut the aft slings and repositioned the vehicle from the 70 degree to the 90 degree hang angle. This sequence was flown on the final V-131R flight. Unfortunately the pitch rate actually increased. The pre-flight predictions for max pitch rate were 74 degrees per second for repo 1 and –75 degrees per second for repo 2. The actual flight rates were 85 degrees per second for repo 1 and –110 degrees per second for repo 2. Unfortunately, no further work was done due to program cancellation.

The reposition event also contributed to other vehicle dynamics due to the rotation of the vehicle-parachute system as the flight path goes to 90 degrees. The vehicle would twist under the drogue. Model simulations indicated that a tail-slide phenomena induced the yaw rate. Due to the rotation of the vehicle-parachute system, the flight path goes to 90 degrees, inducing a small "swing" velocity at the vehicle. This "tail slide" velocity caused the vehicle flight path angle to be steeper than the system pitch angle. A the vehicle yawed off the wind line, the "tail slide" velocity created a sideslip angle, which in turn caused a yaw moment. The yaw rate experienced on each flight ranged from 37 to 71 degree per second, resulting in multiple revolutions. A round parachute is unable to provide a restoring torque to counter the yaw rate. Although the yaw rate was within acceptable limits for astronauts, the program believed it was critical to reduce the dynamics as much as possible. The changes to reduce the drogue reposition pitch dynamics discussed above did to reduce the number of revolutions from 7.5 revolutions on the second flight of V-131R to 4.5 revolutions on the third and final flight of V-131R. A more definitive technique to null the yaw rate was needed. The proposed fix was to utilize the existing spacecraft's cold jets reaction control system to null the yaw rate. The cold jets reaction control system was incorporated into V-131R, however, the program was cancelled prior to conducting a flight test.

Weight was another driver to the drogue parachute design given the criticality of a spacecraft's weight. The location of the drogue compartment in the aft portion of the vehicle resulted in the addition of forward ballast. The Kevlar suspension lines, radials, reefing lines, vent hoop, and risers were all replaced with Zylon. Zylon has a higher strength to weight ratio than Kevlar, resulting in significant reduction in parachute and ballast weight[6]. However, Zylon loses strength when exposed to light[8], which resulted in more frequent suspension line replacement. Spectra was identified as a possible candidate material to replace Zylon, but no testing was done due to program cancellation.

Parafoil

The parafoil was used to land the vehicle. The challenge to develop a repeatable deployment was the biggest challenge of the X-38 program. The details of the design and testing has been significantly documented in several AIAA papers[1,2,3,5,8,9,10,12]. The final CRV configuration was the 7,500 ft^2 parafoil. The program was successful in demonstrating a robust 7,500 ft^2 parafoil that had repeatable, low dynamic deployments, which was truly a remarkable achievement.

Backup Drogue and Main Parachutes

A backup parachute system was required for the V-130 series flight tests at EAFB[1]. This system developed consisted of parachutes that had been fabricated and tested by other programs to limit system costs. The pilot and mortar, described in an earlier section of this paper, were obtained from the Space Shuttle Orbiter drag parachute system. The drogue had been developed and tested by Sandia National Laboratory for potential use as a weapons parachute. Sandia completed twelve airdrop tests, three rocket launched tests, and five environmentally conditioned sled tests. The program had been cancelled, making two tested parachutes available. The parachute was a 26 ft nylon/Kevlar ribbon parachute having a design load of 72,200 lbs and a deployment dynamic pressure range of 460 to 1,365 psf (and was tested to 1,713 psf to demonstrate margin). The design load and dynamic pressure requirements for X-38 were 40,000 lb and 430 psf. As result, the parachute was overdesigned and therefore heavy, but because parachute weight was not an issue for the V-130 series vehicles, the drogue was an excellent choice.

Similarly, the backup main parachute selected was a parachute designed and tested for another program. The parachute was proposed as a lighter-weight replacement for the Space Shuttle Solid Rocket Booster recovery parachute, however, the Shuttle program did not approve the change to the lighter-weight parachute. Therefore, the parachute was obtained by the X-38 program. The parachute was a 124 ft hybrid ribbon/solid parachute made of nylon and Kevlar components, with a design load of 210,000 lb, which was well beyond the X-38 design load requirement of 80,000 lbs.

These parachutes were combined into making the X-38 backup parachute system. Three drop tests were performed[1]. Figure 18 shows the platform configuration for the first two drops. The round parachute compartment in the V-130 series vehicles was simulated with a round metal can secured to the deck of the test tub. In the figure, the brown can is partially obscured by plywood. The plywood was needed to provide a surface to which the slings could be secured. There were no parachute failures, however, two of the three drops experienced problems with the drogue release function. The first test differed from the parafoil drop tests in that the sink rate was much higher, which caused the pneumatic timers in the event sequencer to not function properly. The load impacted before the timers expired. The pneumatic timers were subsequently replaced with electronic timers.

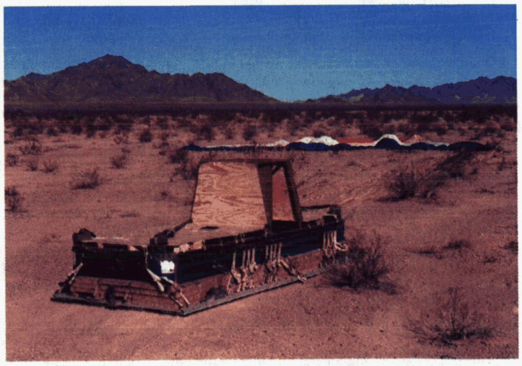


Figure 18. Platform configuration for backup parachute drop tests.

The second drop test failure was on the doghouse, described earlier in the paper. Fortunately, the backup parachute system was never used on any of the V-130 series flight tests.

GUIDANCE, NAVIGATION, AND CONTROL SYSTEM

The parafoil GN&C system evolved during the X-38 program. Initially, the X-38 platform drop test program used a GN&C system provided by SSE. This was a standalone system, consisting of a flight computer, global positioning system (GPS), magnetic compass, barometric altimeter, and an uplink modem. Modified Warn truck winches, provided by Pioneer Aerospace, were used to steer the parafoil and to perform the dynamic flare maneuver. The control surfaces of the parafoil were the outer 25% of the trailing edge, thus utilizing differential drag to effectively steer the canopy. The control stroke setting was 80% of the stall stroke setting. A Trimble GPS card provided the primary navigation parameters (i.e. position, altitude and heading data) for the GN&C. In the event of a GPS failure, the software navigated by dead reckoning using the compass and barometric altimeter data. The compass was a KVH Industries' C100 electronic compass. A laser altimeter, built by Regal of Austria, was the ground proximity sensor used by the PGNC to trigger the flare. The laser altimeter provided excellent accuracy of +/- 10 cm. A heater was installed on the laser altimeter's box to keep the electronics within the operating temperature specifications.

This parafoil GN&C system was installed for the V-131 and V-132 flight tests, however the primary navigation data was provided from a Honeywell integrated INS-GPS system. These tests were successful, but the program wanted to integrate the parafoil GN&C software with the spacecraft avionics system. The program accomplished this by replacing the SSE software with software built by ESA's Astrium Aerospace. This software was tested on the Buckeye powered parachute prior to each flight test of V-131R. All three V-131R flight tests successfully demonstrated the parafoil GN&C landing system.

To continue testing parafoil GN&C system, the avionics on the platform test articles had to be changed. Southwest Research Institute, which provided the Buckeye powered parachute and its auto flight avionics, replicated their avionics system for use on the platform test articles, interface with the X-38 sensors and effectors, and host the GN&C software. This provided an excellent test bed on the last six platform drops to evaluate hardware and software planned for the CRV spacecraft, including a radar altimeter and improved winches.

To meet the spacecraft environment conditions, the program selected Honeywell's HG7705 radar altimeter to replace the laser altimeter. Although the radar altimeter was less accurate, it provided sufficient accuracy of +/- 2 meters to trigger the flare maneuver. Testing of the radar altimeter was performed on the Buckeye. The challenge in testing the radar altimeter on a platform drop test, was that the altimeter would have to be deployed after platform extraction from the airplane. A deploy mechanism was installed on the air data probe housing located in forward end of the platform. The deploy mechanism was held in place by a pyrotechnically initiated pin retraction device, similar to the device used to release the hatches on the V-130 series vehicles. An event timing sequencer was used to fire redundant NSIs that in turn ignited the pyro device 100 seconds after load extraction from the airplane, allowing the strut to stroke and deploy the mechanism. Figures 19 and 20 show the mechanism in the stowed and deployed positions. One drop test with the radar altimeter was performed prior to the cancellation of the program. The radar deployment was slow due to insufficient strut force, however, the mechanism did achieve reach its fully deployed position. Radar altimeter successfully triggered the flare.

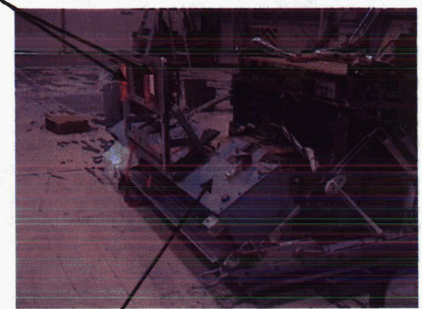


Figure 19. Radar altimeter mechanism in stowed position

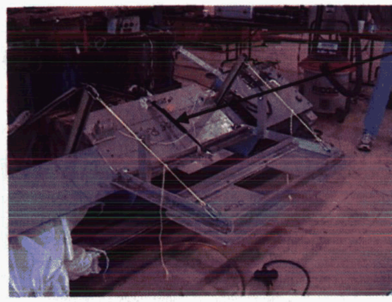


Figure 20. Radar altimeter mechanism in deployed position

Another significant change was replacing the Warn truck winches with a winch design that was more appropriate for a spacecraft application and that provided improved landing flare performance. The new winch was a modified 270 Volt brushless DC aircraft hoist, capable of retracting the 18 ft of control line in 5 seconds, which was a significant improvement over the Warn winches at 15 seconds. The installation of the two winches is shown in figure 21. The black pelican box between the two winches contained the battery pack to operate one winch. The other battery box was located in a metal box mounted on the platform behind the test tub. The battery was constructed by stacking commercial off-the-shelf NiCad cells (Sanyo CP-2400SCR, sub C cells) in a parallel/series arrangement. Each battery box contained two parallel strings; each string had 210 cells connected in series inside Nomex insulating tubes. One of the boxes is shown in figure 22. The winches were used successfully on the final six platform drops.

Figure 21. 270 Volt winches installed in test tub.

Figure 22. 270 Volt winch battery.

The GN&C software used to fly the parafoil underwent extensive testing, modification, and improvement during the X-38 flight test program. The basic approach of the software logic was similar to other GN&C designs.[4] The logic developed a reference trajectory to reach the target, used guidance to make trajectory adjustments in response to performance and flight conditions, used navigation to determine its location, and used control logic to fly the reference trajectory. The reference trajectory is shown in Fig. 23.

The first guidance phase, shown in figure 23, was the target acquisition turn. The guidance then exited the turn onto a homing leg. The next phase was the energy management circle (EMC) entry turn. While on the EMC, the guidance modulated the EMC's diameter in response to wind or parafoil performance dispersions. At the appropriate location, guidance initiated the EMC exit turn onto the predetermined final heading., established by the winds of the day for a headwind landing. On final approach, the guidance continued to minimize cross track error. Ten seconds prior to flare, 40% flaps was commanded to minimize dynamics before the flare maneuver. The radar altimeter was used as the trigger for the software to initiate the flare.

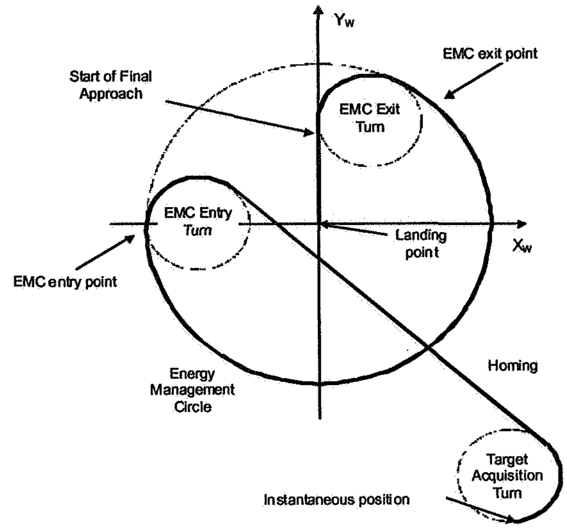


Figure 23. PGNC reference trajectory

The GN&C was designed to autonomously fly the entire flight trajectory from built in turn release to landing, but the system had a receiver that provided a manual override capability to control the parafoil flight from a ground station. The ground station could also receiver downlink from the GN&C system to perform real-time monitoring of the system and the test article's ground track.

TESTING TIMELINE

The testing process evolved during the parachute test program. A Test Configuration Review process was used to drive the test planning for all tests. For a full-scale parachute test, the test planning was more complex and included defining and approving the test article configuration, test article weight and balance, configuration changes, anomaly resolution, drop test aircraft, test objectives, test timeline, test success criteria, test team duties, performance predictions, predicted loads and safety margins, range services, flight rules, manual parafoil maneuvers, and procedures. This review process was started three to four weeks, depending upon the complexity of the drop, prior to the planned drop date. A final review was held on the day before the drop to close any open issues and to obtain the approval to proceed with the drop.

The ground test team consisted of the test director, a parafoil pilot (to fly the parafoil remotely if required), a timer to make the time calls for each manual maneuver, GN&C ground station monitors, a test article manager (i.e. the senior rigger), a safety observer, and a test range project engineer. The test director managed the test and communicated with the airborne team members, which consisted of an instrumentation engineer and a chase engineer. The instrumentation engineer flew with the load to activate the instrumentation, described in the following section of this paper. The chase engineer flew in a helicopter, which was used to fly to assist in identifying problems with the parafoil not visible from the ground, provide real-time assessment of the parafoil and parafoil GN&C performance, and to obtain video and still photography for documentation and post-drop analysis. Wescam video equipment was installed on the helicopter to provide a good source of video of the drop. Chase also kept track of the released drogue to assist in timely recovery of the parachute and provided guidance to the ground test team on the optimal route to take to the load after the drop.

The timeline on the day of the drop test started with receiving balloon winds aloft data from the drop zone about 3 hours prior to the drop time. The winds were used as input in two tools: a GN&C mission-planning tool and a footprint tool. These tools were used to select the drop coordinates that would enable the GN&C to fly to the target landing point and ensure that the released drogue parachute would land on the range. As the mission plan was developed, members of the ground team set up the ground station equipment and radios. Balloons were sent up once an hour prior to the drop to confirm the release coordinates and at the drop time to get the wind data for post-drop trajectory analysis. Flight cards used by chase were updated with the final changes. A crew briefing was held with the range, drop aircraft crew, instrumentation engineer, chase, and the test director to finalize the test plan, drop coordinates, communication frequencies, and call signs and to review contingency plans.

After the GPS coordinates for the drop, target and drop points, the landing heading, winds aloft data, and other GN&C data were loaded into the flight computer and the final test article preparations were completed, the rest of ground test team flew to the drop zone in a helicopter. Then the drop aircraft took off. At least one dry run was needed to confirm that the chase helicopter was in position, that the on-board instrumentation was within the drop rules, and that the required number of range tracking and ground-to-air video cameras were tracking the drop aircraft.

After the test director gave to go for the drop, the team monitored load extraction from the cargo aircraft and the parachute deployment sequence. The ground station personnel monitored downlink from the test article to evaluate the GN&C performance and load ground track. If the drop test included manual maneuvers, the test director would execute a maneuver card, which consisted of planned manual flap maneuvers to obtain aerodynamic performance data (e.g. turn rates, stall characteristics, lift, or drag) for correlation with the simulation models. A timer kept time to ensure that each maneuver was done for the intended length of time to ensure that any dynamics associated with the maneuver had damped out prior to moving to the next maneuver. After completing the card or reaching the maneuver cut-off altitude, the pilot commanded the GN&C back to auto so that the GN&C could fly the parafoil to the target, turn into the wind, and perform a dynamic flare. The manual control capability was also used to override the GN&C to control the steering of the parafoil to stay on the range or to inhibit flare due to a parafoil or GN&C failure. A safety person monitored the released drogue to ensure that chase did not come close to the drogue.

Following the drop, the ground test team convoyed to the load via a route suggested by chase. GPS coordinates were taken of the load and drogue landing sites to evaluate the effectiveness of the footprint tool and the sink rates used in the tool. The load was secured, the parafoil was disconnected and put into a bag, and recorded data was downloaded. The recovery of the drogue was more complicated when the drogue had zylon components. Exposure to ultraviolet light severely degraded zylon's strength. After the drop, the drogue recovery personnel were taken to the drogue's landing site in a helicopter to put the drogue in a bag as soon as possible. The drogue could then be moved either by lifting the bag into the bed of a truck or by a sling suspended under the helicopter.

One of the unique features for the V-131R flight test was the use of a van to simulate the CRV cockpit in order to include astronaut participation in the flight test process, to evaluate crew displays and controls for CRV, and to have an astronaut perform manual flight maneuvers of the parafoil during a flight test. Figures 24 shows the crew inside the van. During the final flight test, the crew did successfully execute several maneuvers from the van.

Figure 24. Crew station in van.

INSTRUMENTATION

Instrumentation was installed on the test articles to gather data to needed to validate simulation models and preflight loads predictions, and to generate post-flight trajectory reconstructions. On the full-scale parafoil platform tests the instrumentation included an accelerator package, 50 g and 10 g impact recorders, winch battery voltages and currents, winch position, air data probe, pitch sensor, cameras, and load cells. A differential GPS was flown to obtain test article tracking information. Cameras provided valuable views of parachute deployment. The types of cameras used included high-speed cameras, film cameras, and "lipstick" cameras. These cameras were mounted to view parachute deployment. Early in the development drop testing, these camera views were essential to identify failure mechanisms that occurred during deployment. An infrared camera was also incorporated on two platform drop tests to evaluate their use as means for the astronauts to monitor parafoil deployment and inflation in the event of a night landing. The cameras did provide usable views of the parafoil.

Load cells were used in many locations. Strain links were installed in the drogue and parafoil slings, which was typical hardware used in parachute testing. The program developed a small load cell, called the Tension Measurement System (TMS)[11], to record loads during deployment and steady flight. TMS units were installed on the parachute deployment lines to capture the peak snatch loads and on the parafoil's dispersion risers, crossover slings, control lines, and leading edge of the canopy's lower surface to verify the loads and material safety margins. These loads had not been measured on previous parafoil programs.

A GPS repeater was used on the drop aircraft to keep the GN&C's GPS locked on while the load was in the aircraft. Otherwise, the GPS signal would have been lost until the load was extracted from the aircraft, resulting in a delay in acquiring the satellites.

NASA also developed a parafoil inclinometer system[12], which used accelerometers attached to the lower surface of the parafoil canopy. Data from the accelerometers was collected and stored in a data logger, also located on the canopy. The data, valid during steady state flight, measured the parafoil's trim angle of attack. Trim angle of attack was important to predict, evaluate, and optimize a parafoil's flight performance.

For subscale and component-level testing, instrumentation, as appropriate, was used. For example, the leading edge TMS was used on the subscale parafoil tests, providing critical deployment loads needed to assess potential solutions for deployment problems.

A technique was developed to determine if the reefing cutters had inadvertently fired during the packing process. The sound of a cutter firing during the packing process would not be heard; the sound would be muffled by the parachute material. Initially a Teflon cord was routed through the cutter aperature and tied, forming a loop. The loop extended outside the pack, where the rigger could pull on the loop. If the cutter had fired, the cord would have been cut and would pull free during the pull test. As the pack density increased during the project, it became increasingly difficult to do this pull test. Therefore a new technique was developed. The cord was replaced with a wire. A continuity test was performed to determine if the wire had been cut by the cutter. This provided a more positive means to verify that the cutters had not been fired during the packing process.

Recovery of released parachutes was an issue. Parachutes needed to be recovered not only for reuse, but also for inspection to look for damage. Released parachutes drift with the wind and can be difficult to locate on the ground, especially if the release occurred at a high altitude. One 60 ft drogue parachute was lost, resulting in the need to incorporate a technique to assist in locating parachutes. The technique selected was to install a tracking beacon onto the parachute. This technique enabled the recovery of all subsequent parachutes.

The tracking beacon, shown in figure 25, was the Telonics RB-10 beacon commonly used to track animals. The enclosure was watertight and was sturdy enough to tolerate deployment and hard landings. This was a very robust device, weighing about 129 grams. Each beacon was powered by a 9 Volt alkaline battery. The antenna was a quarter wave stainless steel flexible whip. The beacon and its antenna were installed in a pouch, shown in figure 25, to aid in installation of the unit on a sling of the parachute to be released. The portion of the pouch that housed the antenna had Velcro so that the pouch could be opened for easy insertion of the antenna and then resealed with the Velcro. Prior to the drop test, the external magnetic arming slug was removed to activate the beacon's internal on/off switch. The beacon transmitted with a low power output of 30 mW, and therefore, did not interfere with any of the on-board avionics or test range systems. Each beacon had one frequency. The frequencies of all of the beacons used ranged from 216.0121 to 217.5528 MHz.

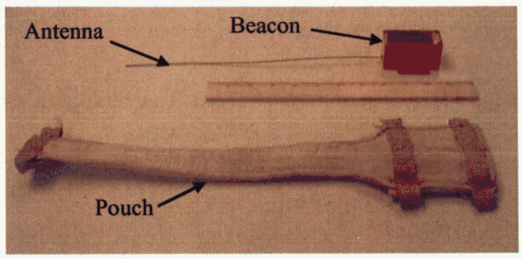


Figure 25 RB-10 Telonics tracking

Figure 26. TR-4 Receiver

The tracking beacon receiver, shown in figure 26, was the Telonics TR-4 receiver, designed for easy field use. The receiver antenna, shown in figure 27, was the RA-2A antenna, which was a directional, hand-held antenna. To use the receiver, the operator selected the channel for a specific beacon using push-switches. The operator would slowly move the antenna until picking up the beacon signal. The receiver could be used on the ground or from a helicopter. Headphones were needed when the operator was in a helicopter in order to detect the signal.

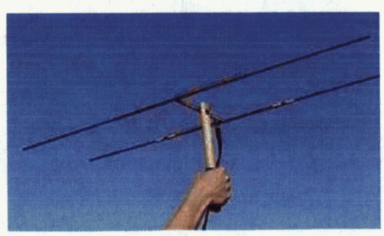


Figure 27. Tracking receiver antenna.

SIMULATION TOOLS

Simulation models were developed by NASA to support design development, provide pre-drop performance predictions, and perform post-drop performance analysis and trajectory reconstructions. These models will also be important in the human-rating process for any future NASA human-rated spacecraft using a parachute system as the primary landing system. The models included the decelerator system simulation (DSS)[13], the parafoil dynamics simulator (PDS)[12], the Brinkley model, and the footprint tool.

The DSS was a six-degree of freedom (6-DOF) model of a round parachute and a 6-DOF model of the vehicle used to predict the drogue sling loads during inflation; parachute disreef event timing, dynamics, and inflation loads; and over-rotation during payload extraction from cargo aircraft. Loads are measured to verify critical material safety margins. Disreef timing is important model to manage the loads during deployment. Dynamics during deployment sequence events can also be improved by selecting an optimal timing sequence.

The over-rotation simulation was developed to bound NASA's acceptable test article center of gravity for the platform configuration and to confirm that it was inside the Army/Air Force's center of gravity box. If the center of gravity was too far aft, the platform would over-rotate immediately upon extraction from the aircraft and could result in the load being upside down, causing the riser to strike the load or become entangled with the load. Damage to the riser could lead to riser failure and loss of the load. Due to this concern, the weight and balance was determined for each load to ensure that the over-rotation was 120 degrees or less. The assembly of the load was modeled using a spreadsheet identifying the location of the components and tub weights. The weight and center of gravity of each load was verified prior to being loaded onto the drop aircraft.

PDS was a 6-DOF rigid body parafoil and a 2-DOF rigid body vehicle model, coupled at the confluence point of the system used to model a parafoil and vehicle system during all phases of flight. These phases included parafoil inflation and transition to forward flight; stage disreefing and brake release; GN&C flight; manual flight maneuvers; and flare and touchdown. This model was used to derive preflight predictions for the expected parafoil performance, parafoil flight time and ground track, and flare performance, and to develop the test plan for manual maneuvers. Parafoil aerodynamic characteristics, such as glide ratio, turn performance, and flare timing, were derived from the model and then incorporated into the GN&C to optimize performance. Additionally, GN&C logic changes were evaluated first in the PDS and then on the Buckeye test article, prior to their incorporation into the full-scale parachute system. During some of the drop tests, planned manual maneuvers were flown to gather aerodynamic data to validate the PDS. After a drop test, PDS was used to determine the longitudinal and lateral-directional aerodynamics and for flight reconstruction to evaluate PGNC and flare performance.

The Brinkley model was developed at Wright Patterson Air Force Base to analyze ejection seat human tolerances. The X-38 program applied this model to evaluate the impact of landing on an ill or deconditioned crewmember by inputting filtered, high impact accelerometer data obtained during a full-scale parafoil landing platform drop or flight test. The drops highlighted in grey are the V-130 series drops. As shown in the table, the program demonstrated improvement in landing impact as the program matured. The drop test designation was "PxDxx". The "P" stood for phase. P2 was phase 2 (the platform drops at Yuma Proving Ground) and P3 was phase 3 (the V-130 series drops at EAFB). The "D" stood for drop and the number after the drop was a specific drop test number. Therefore P2D4 means phase 2 drop 4 (i.e. the fourth platform drop).

Drop Test	Impact Technique	Impact Vel. (fps) Vert.	Horiz.***	Peak g's (filtered) Vert.	Horiz.	Dynamic Response g's** Vert.	Horiz.	Injury Risk Criteria* Healthy	Ill/Injured
P2D4	part. flare	23	30	27	14	32	15	moderate	high
P2D6	No flaps	26	65	51	18	46	17	> high	> high
P2D8a	50% flaps	25	16	40	9	40	9	high	> high
P2D11	50% flaps	24	16	31	10	38	12	high	> high
P2D13	part. flare (33% flaps) with trees	21	73	18	15	20	16	moderate	high
P2D14	L0/R20; 5th Stage Failed.	27	65	41	16	47	17	> high	> high
P2D15	L49/R45% flaps	21	51	21	17	21	18	high	> high
P2D16	L0/R28% flaps	Unknown	Unknown	47	17	55	17	> high	> high
P2D17	50% flaps	22	62	51	20	43	15	> high	> high
P2D18	Back-up Drogue	180	19	60	57	60	57	> high risk	> high
P2D20	55% Flaps	25	37	46	13	38	7	high	> high
P3D1	L70/R60%	17	56	9	8	9	8	low	low
P2D21	98% Flaps	21	50	32	14	30	7	moderate	high
P2D22	Flare	14	54	11	9	12	8	low	low
P2D23	~L80/R70% flaps	23	46	25	8	29	7	moderate	moderate
P2D24	Flare	15	39	11	9	10	8	low	low
P2D25	~L0/R50% flaps	17	58	16	10	19	9	low	low
P2D26	~L0/R50% flaps	15	70	13	9	8	9	low	low
P3D2	Early Flare	18	25	6	6	6	7	low	low
P3D3	Flare	10	41	12	4	5	2	low	low
P3D4	Flare	8	59	12	2	9	1	low	low
P2D28	Early Flare	18	39	22	8	23	7	low	low
			aft IST:	35	8	31	7	low	moderate
P3D5	Early Flare	15	39	21	7	12	6	low	low
P2D32	Early Flare	25	43	21	9	26	8	low	low
P2D33	Early Flare	20	60	18	10	13	7	low	low
P3D6	R50/L0 % Flaps	24	59	17	18	13	13	low	moderate
			aft IST:	30	13	18	9	low	low
P2D35	Early Flare	12	27	11	1	12	2	low	low
P2D37	Early Flare	15	45	16	8	12	6	low	low
P3D7	Early Flare	17	33	13	7	12	6	low	low
P2D38	Flare	8	21	6	3	5	2	low	low
P2D39	L0/R60; 11 cells failed to disreef	22	47	23	13	27	14	moderate	high
P2D41	Flare	9	26	12	2	9	3	low	low
P2D42	Flare	10	43	11	5	10	4	low	low

Table 2. Brinkley model assessment of all drop tests

CONCLUSION

The X-38 program successfully developed and demonstrated a viable parachute system for CRV. In doing so, advancements were made in parachute design, test techniques, simulation tools, and instrumentation that can be applied to future parachute programs.

Acknowledgments

The author would like to thank the X-38 test team and management for the hard work by all in the advancement of parachute systems.

References

[1]Machin, R., Stein, J., and Muratore, J., "An Overview of the X-38 Prototype Crew Return Vehicle Development and Test Program", AIAA-99-1703, 15th CEAS/AIAA Aerodynamic Decelerator Systems Conference, pages 20-37, June 1999.

[2]C. Schroeder Iacomini and C. Madsen, "Investigation of Large Scale Parafoil Rigging Angles: Analytical and Drop Test Results", AIAA-99-1752, 15th CEAS/AIAA Aerodynamic Decelerator Systems Conference, June 1999

[3]Bennett, T. and Fox, R., "Design, Development & Flight Testing of the NASA X-38 7,500 Ft^2 Parafoil Recovery System", AIAA-2003-2107, 17th CEAS/AIAA Aerodynamic Decelerator Systems Conference, May 19-22, 2003

[4]Strahan, A., "Testing of Parafoil Autonomous Guidance, Navigation & Control for X-38", AIAA-2003-2115, 17th CEAS/AIAA Aerodynamic Decelerator Systems Conference, May 19-22, 2003

[5]Machin, R., "Design and Testing of the X-38 Spacecraft Primary Parafoil", AIAA-2000-4312

[6]Behr, V. L., Wolf, D. F., Rutledge, B. A. and Hillebrandt, F. D., "Development of an 80-Foot Diameter Ribbon Drogue Parachute for the NASA X-38 Vehicle," 16th Aerodynamic Decelerator Systems Technology Conference & Seminar, AIAA-2042, Boston, Massachusetts, 21-24 May, 2001.

[7]Stein, J., Machin, R., Wolf, D., and Hillebrandt F., "The Development of a 100-ft Drogue Parachute for the X-38 Spacecraft", AIAA-2005-1679, 18th CEAS/AIAA Aerodynamic Decelerator Systems Conference, May 2005

[8]Maloy, J. and Machin, R., "Space Rating of X-38 Parafoil and Drogue Parachute Materials", AIAA 17th Aerodynamic Decelerator Systems Technology Conference, May 19-22, 2003

[9]Inacomini, C. and Cerimele, C., "Lateral Directional Aerodynamics from a Large Scale Parafoil Test Program", AIAA-99-1731, 15th CEAS/AIAA Aerodynamic Decelerator Systems Conference, June 1999

[10]Inacomini, C. and Cerimele, C., "Longitudinal Aerodynamics from a Large Scale Parafoil Test Program", AIAA-99-1732, 15th CEAS/AIAA Aerodynamic Decelerator Systems Conference, June 1999

[11]Machin, R. and Fitzgerald, S., and Royall, P. and Walcer, M., "Technique for Measuring Parafoil Deployment and Steady State Loads in Dispersion Risers and Leading Edge Reinforcement Tape", AIAA-99-1733, 15th CEAS/AIAA Aerodynamic Decelerator Systems Conference, pages 20-37, June 1999.

[12]Madsen, C. and Cerimele, C., "Flight Performance, Aerodynamics, and Simulation Development for the X-38 Parafoil Test Program", AIAA-2003-2108, 17th CEAS/AIAA Aerodynamic Decelerator Systems Conference, May 19-22, 2003

[13]Cuthbert, P., "A Software Simulation of Cargo Drop Tests", AIAA-2003-2132, 17th CEAS/AIAA Aerodynamic Decelerator Systems Conference, May 19-22, 2003