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ABSTRACT

SPACE SHUTTLE

SOLID ROCKET BOOSTER

LIGHTWEIGHT RECOVERY SYSTEM

The cancellation of the Advanced Solid Rocket Booster Project and the earth-to-orbit payload requirements for the Space Station dictated that the National Aeronautics and Space Administration (NASA) look at performance enhancements from all Space Transportation System (STS) elements (Orbiter Project, Space Shuttle Main Engine Project, External Tank Project, Solid Rocket Motor Project, & Solid Rocket Booster Project). The manifest for launching of Space Station components indicated that an additional 12-13000 pound lift capability was required on 10 missions and 15-20,000 pound additional lift capability is required on two missions.

Trade studies conducted by all STS elements indicate that by deleting the parachute Recovery System (and associated hardware) from the Solid Rocket Boosters (SRBs) and going to a lightweight External Tank (ET) the 20,000 pound additional lift capability can be realized for the two missions. The deletion of the parachute Recovery System means the loss of four SRB's and this option is two expensive (loss of reusable hardware) to be used on the other 10 Space Station missions. Accordingly, each STS element looked at potential methods of weight savings, increased performance, etc. As the SRB and ET projects are non-propulsive (i.e. does not have launch thrust elements) their only contribution to overall payload enhancement can be achieved by the saving of weight while maintaining adequate safety factors and margins. The enhancement factor for the SRB project is 1:10. That is for each 10 pounds saved on the two SRBs; approximately 1 additional pound of payload in the orbiter bay can be placed into orbit. The SRB project decided early that the SRB recovery system was a prime candidate for weight reduction as it was designed in the early 1970s and weight optimization had never been a primary criteria.

Since the 1970's considerable advances in cloth materials have been realized. New fibers have been developed which have a much higher strength to weight ratio than Nylon. Also, canopy loading predictions have been developed which considers each canopy element, individually, rather than using a rule-of-thumb approach. This means all elements of parachutes can now be designed for the exact loading condition they will experience and the design of these parachutes will make use of more efficient materials with lower positive margins. Early trade studies of the SRB parachute recovery system have indicated that new lightweight main parachutes could be used which would be 60% lighter than those currently used to recover the SRBs after each STS mission. The SRB project has committed to an SRB weight reduction of 6000 pounds/SRB. 80% (5000 pounds) of this 6000 pound weight savings will come from reducing the parachute recovery system weight from the current 8500 pounds to 3500 pounds.

This paper describes the design concept for these lightweight SRB parachutes, the design constraints imposed by the STS, the projected weight savings, and design differences from the current parachute design.

STS program requirements require that the terminal velocity (water impact) of the SRB under the three main parachutes remain unchanged. This implies that the new lightweight parachutes maintain the same drag area (C_dA). The new lightweight parachutes will be smaller in diameter so the geometric porosity will be decreased from the 16% of the current parachutes. This reduction in geometric porosity will achieved by reducing the horizontal ribbon spacing and by adding a solid cloth panel to the lower 17% of each gore. Preliminary studies indicate that the addition of the cloth panel may enhance the initial opening and inflation of the parachute. The current main parachutes are sluggish in inflation and about 1 out of 6 flights experiences a "lagging" main parachute during the initial first stage inflation.

The paper further describes the proposed airdrop test program of the new lightweight parachute design and the parameters that will be monitored for each airdrop.

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SPACE SHUTTLE SOLID ROCKET BOOSTER

LIGHTWEIGHT RECOVERY SYSTEM

Background

The U. S. manned space program[1] evolved from ballistic missile technology that existed in the late 1950s. Small one-man Mercury spacecraft were launched atop modified Redstone and Atlas ballistic missiles. The launch vehicles were completely expendable like their ballistic missile predecessors, and although the spacecraft were recovered by parachutes, they were not reused. A very similar approach was followed in the second generation Gemini program. Modified Titan 2 ballistic missiles launched the two-man Gemini spacecraft. The launch vehicles remained expendable, and the more maneuverable spacecraft were also parachute recovered, but not reused. Even the bold advances of the NASA Apollo moon-exploration program followed an evolutionary philosophy in launch vehicle and spacecraft design. A totally new Saturn class of expendable boosters was needed to satisfy the high-energy requirements of trans-lunar trajectories. The three-man Apollo command module possessed even more reentry maneuvering capability than Gemini, and was recovered with a sophisticated parachute landing system[2], but was not reused.

The advent of the NASA Space Transportation System (STS) or Space Shuttle in the late 1960s and early 1970s marked a truly revolutionary change in U. S. manned space flight. For the first time the large number and frequency of planned missions dictated the reuse of flight hardware, based on economic and environmental considerations. Initial concepts proposed totally reusable flyback booster and flyback orbiter combinations. Development cost constraints eventually resulted in the current Space Shuttle[3] configuration. Its spacecraft consists of a flyback, reusable, Orbiter that can carry large crews and heavy payloads, can accomplish extensive reentry maneuvers, and can make gliding aircraft-like landings. Fuel and oxidizer for the Orbiter are contained in an expendable external tank that is jettisoned at near orbital velocities and breaks up on reentry. 80$^+$% of the Space Shuttle thrust for the first two minutes of flight is provided by two Solid Rocket Boosters (SRBS) that are recovered and reused because they are inherently rugged structurally, burn out at a velocity of only about 4000 ft/sec, and land, in the ocean, about 150 miles from the launch point.

Marshall Space Flight Center (MSFC) was given the responsibility within NASA for developing the reusable SRBs and their reusable Decelerator Subsystem (DSS) parachutes. Parachute experts that resided within NASA and its contractors that worked on earlier manned spacecraft landing system developments were consulted for design concepts. The lightweight ringsail parachute designs from the Mercury, Gemini and Apollo programs were considered because of their impressive performance and unequaled efficiency. However, the design requirements[4] for the SRB recovery parachutes were different.

The 180,000 lb reentry weight of each SRB was far greater than the weight of any of the manned spacecraft and over three (3) times the routine parachute recovery weight at that time. Also, parachute deployment would have to be initiated from an unstable and tumbling SRB. The excessively large recovery weight and difficult deployment environment presented a significant technical risk. In addition, NASA's development budget required success with minimal testing. In order to minimize the risk and stay within budget constraints, NASA chose to use proven technology rather than attempt performance optimization that could reduce weight. The decision was also influenced by the relatively low payload weight trade-off for SRB subsystems. A reduction of 10 lb in SRB weight resulted in an increase in Space Shuttle payload of only about one pound, so the incentive for weight saving was not strong. Only the rugged ribbon parachutes, previously developed, for heavy weapon retardation[5] satisfied proven size and strength requirements. The many parallel load paths and small individual element sizes of ribbon parachutes also enhanced damage tolerance and reliability in the severe SRB deployment environment.

A 76-ft ribbon parachute developed for weapon retardation[6] at Sandia National Laboratories (SNL) more closely matched the SRB parachute load and size requirements than any other at the time, so it became the model for the original SRB parachutes. Design parameters for the 76-ft parachute are given in Table 1:

Diameter	76 ft
Number of Gores	80
Porosity	16%
Geometry	20^0 Conical
Construction	Cut-Gore Ribbon
Reefing	14% to 53%
Design Load	120,000 lb
Pack Weight	725 lb

Table I Sandia 76-ft Parachute

The 76-ft parachute had been tested approximately 30 times, so it satisfied NASA's requirement for proven technology. Surplus 76-ft parachutes were also used by NASA to develop ocean retrieval and refurbishment ground-handling procedures and hardware prior to the availability of actual SRB recovery parachutes. Because of experience with the 76-ft and other heavy ribbon parachutes[7,8], NASA retained SNL engineers in an advisory capacity[9] during the subsequent SRB DSS development.

Another example of the reliance on proven technology was the requirement to use only existing mil spec materials in the SRB parachutes. Kevlar materials were in their infancy and no mil spec weaves existed, so only nylon could be used for the designs. Like the SRBS, the parachutes were designed to be reused. The drogue and main parachutes were designed with a reuse goal of 20 uses, and were conservatively certified for 10 uses. Reuse required repair of damaged elements and refurbishment of the parachutes to flight certified condition. In order to facilitate handling of heavy fabric components, the drogue and main parachutes were designed with removable suspension lines, dispersion bridles and risers that were joined, using detachable metal links.

Design parameters for the original SRB parachutes [10,11,12] are given in the following tables:

Diameter	11.5 ft
Number of Gores	16
Porosity	16%
Geometry	20° Conical
Construction	Cut-Gore Ribbon
Reefing	Overinflation Line
Design Load	14,500 lb
Pack Weight	41.5 lb

Table II: Original 1981 SRB Pilot Parachute

Diameter	54 ft
Number of Gores	60
Porosity	16%
Geometry	20° Conical
Construction	Cut Gore Ribbon
Reefing	55% and 79%
Design Load	270,000 lb
Pack Weight	1250 lb

Table III: Original 1981 SRB Drogue Parachute

Diameter	115 ft
Number of Gores	96
Porosity	16%
Geometry	20° Conical
Construction	Cut Gore Ribbon
Reefing	17% and 45%
Design Load	173,300 lb
Pack Weight - Each	1708 lb

Table IV: Original 1981 SRB Main Parachute - One of Three

Diameter	136 ft
Number of Gores	160
Porosity	15.4%
Geometry	20° Conical
Construction	Cut Gore Ribbon
Reefing	16% and 36%
Design Load	150,000 lb
Pack Weight - Each	2160 lb

Table V: 1985 SRB Large Main Parachute - One of Three

At the same time the 136 ft main parachute was being developed, NASA was preparing to fly the Space Shuttle from Vandenberg Air Force Base (VAFB) for polar orbit missions. Filament wound case (FWC) SRBs were developed for the higher energy requirements of these missions. Although the FWC boosters were lighter, they had a more aft center gravity location. The net effect was to cause more nozzle-first reentry attitudes and higher reentry dynamic pressures at parachute deployment altitudes. This more severe environment required the development of new pilot and drogue parachute designs. Design parameters for the FWC pilot and drogue parachutes [12,14] are given below:

Diameter	10 ft
Number of Gores	12
Porosity	18%
Geometry	20° Conical
Construction	Cut Gore Ribbon
Reefing	Overinflation Line
Design Load	32,500 lb
Pack Weight	72 lb

Table VI. 1981 FWC SRB Pilot Parachute

Diameter	52.5 ft
Number of Gores	72
Porosity	20%
Geometry	20^0 Conical
Construction	Cut Gore Ribbon
Reefing	45% and 74%
Design Load	375,000 lb
Pack Weight	1250 lb

Table VII. 1981 FWC SRB Drogue Parachute

Both the FWC pilot [15] and drogue [16] parachutes were overtested and ready for operational use. The drogue overtest produced a maximum load of 471,500 lb at a deployment dynamic pressure of 687 psf. Cancellation of the VAFB missions terminated the FWC program. The special heavy-duty pilot and drogue parachutes were never flown on Space Shuttle boosters.

The development of the FWC pilot and drogue parachutes was combined with that of the 136 ft main parachute to more efficiently utilize personnel and test capabilities. The very large 375,000 lb reefed design load for the FWC drogue forced a minor departure from the "all nylon" design philosophy. The reefing line design load was so large that a reefing cutter redesign would have been required for a nylon reefing line of the required strength. A kevlar line could be cut with the then existing and proven cutter. Because kevlar mil spec materials existed at the time the FWC system was being developed, kevlar was used for the FWC drogue reefing lines. The same technical basis was used to include kevlar reefing lines in the 136 ft main parachutes being designed at the same time.

The STS-25 Challenger accident [17] in January 1986 resulted in some minor SRB DSS design changes. Weight increases and center of gravity changes to the SRBs increased the pilot parachute maximum deployment dynamic pressure to 400 psf. The then existing pilot parachute was modified by substituting higher strength radial and suspension line materials. Rocket sled tests of the modified pilot parachute at dynamic pressures up to 572 psf proved its structural capability, and the modified pilot was flown on subsequent Space Shuttle missions. Coincident with the STS-25 postflight activity, contract responsibility for the SRB DSS was transferred from Martin Marietta/Pioneer Aerospace to United

Technologies USBI. Ripstops were added to the main parachutes shortly after the STS-26 return to flight. The use of ripstops to localize deployment damage had been studied earlier [19], and they were added as part of the return to flight improvements. Extensive CAN0 [20] and NASTRAN stress analyses and development testing were used to optimize the ripstop strengths and locations, and the ripstops' effectiveness in localizing damage has been demonstrated on several flights.
As of March 1995 the Space Shuttle has flown successfully on 68 missions. No SRBs have been lost due to parachute failures. The 54 ft drogue parachute has been reused 10 times as planned, and recertification for more uses is in process. The 136 ft main parachutes have been reused a maximum of 7 times. During the operational lifetime of the Space Shuttle (from 1981 to 1995), NASA and its DSS contractors (Martin Marietta and now USBI) have gained extensive experience in the flight and retrieval environments for the parachutes and in their refurbishment and reuse.

The Lightweight Parachute System Concept

Mission requirements for the Space Station required more payload capability for the Space Shuttle. NASA initiated development of the Advanced Solid Rocket Motor (ASRM) to provide the additional performance. Cancellation of the ASRM program in 1993 initiated new searches for ways to increase payload. One proposed method was to eliminate the SRB DSS entirely on a few missions to maximize the payload increase on these flights. The penalty, loss of two $40 million SRBs per flight, was a unacceptable price to pay. A compromise proposal was to reduce SRB recovery system weight to an absolute minimum and still retain a high probability of successful recovery.

A 1200 pound increase in payload per flight was needed for some missions. Because of the 10 pounds of SRB weight per pound of payload tradeoff, 6000 lb weight savings was needed on each SRB, most of which (5000 lb) had to be removed from the recovery system. Preliminary studies showed that the weight reduction could be achieved, but only if drastic and revolutionary design changes were made.

Management and Design Approach

When schedule and cost constraints were considered along with the necessarily very large weight reductions, it became clear that a modification of the existing NASA/USBI organization that provided successful SRB flight operations would be required. NASA and USBI managers formed a small team of personnel for the development task. Frequent team or sub-team meetings were held to insure good communication. The brief meetings only addressed specific agenda issues, most of which were resolved immediately, and only directly involved people attended. Appropriate NASA and USBI personnel kept their management informed of team progress. The infrequent formal management reviews were brief and concentrated on making positive contributions to the development program. Design analyses for the development program were shared between NASA and USBI engineers. Analysis tasks were performed where the best capability existed. Critical tasks were sometimes duplicated to insure correct solutions and the final results were agreed upon by the knowledgeable analysists.

Manufacturing of the development parachutes also became part of the team effort. Design analysis, design and manufacturing development all took place concurrently. The result was parachutes that satisfied performance requirements and could be manufactured efficiently. Innovative design and manufacturing suggestions were encouraged from all participants, including sewing and rigging technicians. Early development parachutes were manufactured to sketches and preliminary drawings. Formal signature approvals that could cause delays while adding no value were deferred. Computer Aided Design (CAD) tools were used extensively, and preliminary drawings were distributed by computer network systems to save time.

Design Approach

Design requirements for the LWP system were:

1) Maintain existing 75 fps SRB water impact velocity.
2) Stay within SRB structural interface constraints
3) Maintain 1.5 factor of safety on parachute fabrics
4) Achieve 5000 lb weight loss per SRB

Secondary design goals were to minimize cost per flight by developing efficient manufacturing methods and reusing parachutes as often as possible. A design goal of 10 uses was selected for the LWP system (like the existing system). Some uncertainties exist because the new materials selected to minimize weight do not have an established reuse record in the SRB flight, recovery and reuse environment.

In order to accomplish the large weight reductions, extensive use of high strength to weight ratio kevlar and Spectra materials was planned from the beginning in the new parachutes and deployment bags. Technora is also being evaluated for use in the, planned lightweight, drogue and pilot parachutes.

New fabrics have been designed and woven whenever existing materials did not meet efficiency and weight reduction goals. A new 420 lb selvage ribbon was woven from 100 denier yarn for the LWMP mid-radial area. A slightly modified version of a commercially available kevlar webbing rated at 3800 lb was used for the LWMP radial and suspension line material. The low surface frictional quality of Spectra suggested its use as an attractive deployment bag material. Spectra was thus selected as the baseline material for all deployment bag walls, replacing the two-layer Teflon lined nylon in the existing bag walls. Similarly, nylon deployment bag reinforcements were replaced by kevlar reinforcements in the new deployment bags.

More efficient canopy design is also planned for the new pilot, and drogue parachutes. The new canopies remain primarily ribbon designs because of damage tolerance and ease of repair considerations. More efficient continuous ribbon type construction has replaced the heavy cut-gore construction in all parachutes, even in the 123.5 ft new main parachute. Building the large continuous ribbon main parachute has not proven to be a major problem when innovative manufacturing methods are used.

The search for higher efficiency also led to the selection of shaped-gore canopies over the traditional 20 degree conical canopies of the existing system. In response to a highly respected recommendation,[21] quarter spherical shaped gore approximations are being used. The new main parachute utilizes a penta-conical (5 conic angles) approximation to a quarter sphere. Preliminary stress analyses have shown that for the same inflated diameter and hence same drag area as an equivalent conical canopy, the shaped gore canopy lowers overall ribbon loads. The result is a substantial weight saving or increase in margin of safety in the horizontal ribbons. An exact quarter spherical constructed shape is planned for the new drogue parachute. The reluctance of parachute designers to use complex gore shapes, because of the tedious calculations required, is no longer justified. Modern computer aided design (CAD) tools make a quarter-spherical canopy as easy to design as a simple conical shape.

Another innovative feature of the new parachutes is the alternate vent line stacking sequence used. On the existing SRB parachutes, the traditional spiral stacking sequence is used that progresses in one direction only around the vent band. On very large parachutes like the 136 ft SRB main parachute, the spiral stacking sequence causes excessive three-dimensional porosity in the vent. This results, in severely reefed cluster applications, in generally sluggish in initial inflation and has a tendency for lagging parachutes to temporarily collapse. A lead parachute can then experience excessive loads. The new method alternates the direction of vent line stacking around the vent band. A very stable interwoven vent line stack results that remains imporous even when canopy shapes are distorted in cluster use.

Development Testing methods

Extensive seam and joint testing is accompanying the concurrent design and manufacturing development. High efficiency is required in all sewn joints, regardless of whether they are in minimum margin of safety elements. The small cost and effort required to develop efficient sewn joints is easily justified by the more robust structural load and reuse capability designed into the parachutes. High joint efficiencies must be repeatable in a realistic manufacturing environment as well as in laboratory test specimens.

All SRB parachutes have relatively high deployment or bag-strip velocities. For the pilot and drogue parachutes the large range of deployment dynamic pressures is the cause. Deploying the main parachutes directly with a large drogue parachute to minimize altitude loss causes a similar environment for the mains. Rocket sled tests were used to develop successful deployment bag designs and rigging techniques for the filament wound pilot and drogue parachutes. Reefing cutter deployment dynamics are considered more critical for the new lightweight parachutes. The shock loads generated by stopping a reefing cutter mass with a stiff kevlar suspension line are being investigated with a simple dynamic test setup. Realistic deployment velocities are achieved by stretching nylon webbing on the long defoul deck at the KSC PRF. By instrumenting the reefing cutter with an accelerometer and the suspension line with a load cell, the required quantitative data is being recorded and analyized.

Another innovative and low cost test method is being used to measure drag and dynamic loads on pilot parachutes, small-scale main parachutes and drop test programmer parachutes. The parachutes are deployed from a truck mounted tower while recording airspeed, loads and documentary video data. These simple tests have been invaluable in providing preliminary experimental data quickly and at low cost prior to the more expensive drop tests.

Low cost and tight and predictable schedule requirements are also influencing the drop test planning for the light weight parachute system. The original SRB DSS drop tests utilized the NASA B-52 aircraft flown out of Edwards Air Force Base. Tests were conducted at the National Parachute Test Range at El Centro, and the Naval Weapons Center at China Lake. Both test series used special a 50,000 lb drop test vehicle (DTV) suspended from a B-52 wing[22]. The original DTV was designed to test not only the pilot, drogue and main parachute cluster, but also many aspects of the actual SRB deployment hardware. Major portions of the DTV electronics hardware and the special equipment required to load a DTV on a B-52 wing, in the early 1980's, are no longer operational. Also, the NASA B-52 is a one-of-a-kind aircraft whose availability could not be guaranteed with high assurance.

The drop test program for the SRB light weight parachute system fits within constraints of existing U.S. Army airdrop procedures using C-130 aircraft. The large number of routine drops of this type provided both low cost and high assurance that aircraft and flight crews would be available when needed. The U.S. Army Proving Grounds at Yuma is being used as the test range because of the large number of similar air drops conducted there. The previously used DTVs have been modified to a much simpler configuration that could be dropped from a C-130 aircraft using standard air drop hardware. A combination of range supplied data acquisition systems and commercially available instrumentation and onboard recording equipment is being used. The planned test program is comprised of four single parachute tests of the new main, three tests of the new drogue parachute and two tests of the new pilot parachute.

New Parachute Development Status

The LWP development program formally began in April 1994 to support a June 1997 launch date. Inventory requirements for the six-main-parachutes-per-flight launch schedule dictated the development of the new main parachute first. Initial designs considered were conical ribbons and modified conical ribbons with solid panels near the skirt to increase full-open drag area. More radical departures from the SRB recovery experience, like ringsails, were ruled out because the development and manufacturing schedule did not allow major design changes once the program began. An additional search for efficiency led to considerations of multi-conic approximations to a quarter spherical shaped gore design. The final design selected has five nearly equal length conic segments. Design parameters for the lightweight main parachute are given in the following table:

Diameter	123.5 ft
Number of Gores	126
Porosity	10 %
Geometry	Penta Conical
Construction	Continuous Ribbon/Solid
Reefing	17% & 46%
Design Load	210,000 lb
Pack Weight - Each	760 lb

Table VIII: 1995 SRB Lightweight Main Parachute - One of Three

The first prototype Lightweight Main Parachute (LWMP) canopy was delivered by Irvin Industries in January 1995. Suspension lines and risers were attached at the Parachute Refurbishment Facility (PRF). The completed parachute was then used for packing trials and final design iterations to the kevlar/spectra deployment bags manufactured at the PRF. The first drop test was completed successfully as scheduled on March 8. A maximum load of 210,000 lb on the first reefed stage was recorded. Damage to the upper edge of some solid panels was caused by load transfer from the mini-radials of the ribbon part of the canopy. Because the measured drag area is greater than desired, a simple solid panel modification will be made to remove the damage mechanism for the next test. A slot will be added at the top of the solid panels to uncouple the fabric from the ribbon part of the canopy. A second slot will be added in the center of each solid panel to limit the full open drag area and overinflation.

Only preliminary design estimates are available for the lightweight pilot and drogue parachutes at the time this paper was written. Final size and weight values will depend somewhat on ongoing trajectory optimization studies and the degree of success achieved in developing new materials needed

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