EXPLOSIVE FRACTURING OF AN F-16 CANOPY FOR THROUGH-CANOPY CREW EGRESS

BY

Laurence J. Bement
NASA Langley Research Center

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ABSTRACT

Through-canopy crew egress, such as in the Harrier (AV-8B) aircraft, expands escape envelopes by reducing seat ejection delays in waiting for canopy jettison. Adverse aircraft attitude and reduced forward flight speed can further increase the times for canopy jettison. However, the advent of heavy, high-strength polycarbonate canopies for bird-strike resistance has not only increased jettison times, but has made seat penetration impossible. The goal of the effort described in this paper was to demonstrate a method of explosively fracturing the F-16 polycarbonate canopy to allow through-canopy crew ejection. The objectives of this effort were to: 1. Mount the explosive materials on the exterior of the canopy within the mold line, 2. Minimize visual obstructions, 3. Minimize internal debris on explosive activation, 4. Operate within less than 10 ms, 5. Maintain the shape of the canopy after functioning to prevent major pieces from entering the cockpit, and 6. Minimize the resistance of the canopy to seat penetration. All goals and objectives were met in a full-scale test demonstration. In addition to expanding crew escape envelopes, this canopy fracture approach offers the potential for reducing system complexity, weight and cost, while increasing overall reliability, compared to current canopy jettison approaches.

To comply with International Traffic in Arms Regulations (ITAR) and permit public disclosure, this document addresses only the principles of explosive fracturing of the F-16 canopy materials and the end result. ITAR regulations restrict information on improving the performance of weapon systems. Therefore, details on the explosive loads and final assembly of this canopy fracture approach, necessary to assure functional performance, are not included.

INTRODUCTION

Many current fighter aircraft use canopy jettison approaches to clear an uninhibited path for crew egress. This approach uses pyrotechnic (explosive or propellant-actuated) devices to first activate latch release mechanisms to free the canopy assembly from the airframe, and then jettison the assembly with piston/cylinder thrusters or small rocket motors mounted at the forward edge of the assembly. The canopy pivots around aft hinge points. Seat ejection catapults are not initiated until the canopy has pivoted far enough to insure that the seat and canopy will not collide. How quickly the canopy assembly is jettisoned depends on aircraft attitude and forward velocity. A pitch-down attitude with a flight vector to produce a load on the canopy would resist jettison. Also, if the aircraft has a low forward velocity, there would be a minimal aerodynamic assist on the canopy. Some aircraft, such as the F-15, employ a backup approach to canopy jettison by using frangible acrylic canopies and designing the seat to "punch through" to insure egress. The Harrier (AV-8B) aircraft, a vertical takeoff and landing aircraft, utilizes an interior-mounted explosive cord to fracture acrylic canopies to assure an immediately available, unrestricted through-canopy egress path to reduce crew ejection time. However, on activation, this explosive cord creates explosive pressure waves and peppers the crew with high-velocity fragments from the explosive's metal sheath and from the 3/8th-inch width explosive holder. The crewmembers also face potential harm from the fractured pieces of canopy material.

Canopy jettison approaches introduce a higher degree of complexity over through-canopy egress. The advent of using polycarbonate canopies to resist bird strikes eliminated the possibility of either "punching through" the canopy or applying the Harrier approach. However, current projections of thickness and weight of these canopies indicate that thrusters and rocket motor jettison approaches are reaching capability limits. Furthermore, canopy release and jettison approaches require 3 to 4 mechanisms, such as latch actuators, thrusters and rocket motors. For redundancy, each of these mechanisms requires two inputs.

A reliable method of severing polycarbonate to allow through-canopy crew egress would reduce egress time to expand escape envelopes, simplify aircraft systems and potentially reduce system weight.

The goal of the effort described in this paper was to demonstrate a method of explosively fracturing the half-inch thick polycarbonate portion of the F-16 canopy to allow through-canopy crew egress.

The objectives for canopy fracturing were to:

1. Mount the explosive materials on the exterior of the canopy within the mold line
2. Minimize visual obstructions
3. Minimize internal debris on explosive activation
4. Operate within 10 ms (the seat requires at least 30 milliseconds from catapult initiation to reach the canopy)
5. Maintain the shape of the canopy after functioning to prevent major pieces from entering the cockpit
6. Minimize the resistance of the fractured canopy to seat penetration

The approach for this development, initiated in references 1, 2 and 3, was to utilize augmented shock wave severance principles. Parallel explosive cords, as shown in figure 1 in which the cords are proceeding into the plane of the paper, are initiated simultaneously. The several-million psi pressure generated by the explosive cords transfers into the polycarbonate and the resulting incident and reflected explosive pressure waves augment to induce the material to fail in tension. The preliminary effort began with evaluations on commercial grade polycarbonate. Then the F-16 canopy was selected for evaluation, since it is the first production polycarbonate canopy, and service-scrapped canopies were available. Small (6 X 6-inch plate) specimens were cut from flat stock and canopies for testing. The evaluation progressed to small-scale (18 to

30-inch dimension), "mini-panels" to determine the performance of complete fracture patterns. Finally, three full-scale canopy tests were conducted.

TEST MATERIALS

This section describes the polycarbonate material and F-16 canopy tested, as well as the explosive and the explosive holder used in the tests.

Polycarbonate - Polycarbonate is a long-chain, organic compound. It has no clear melting point, similar to glass. It simply gets softer under elevated temperatures until it can be shaped, and finally, the viscosity becomes low enough to allow flowing. However, it has a temperature/cycle memory. Each time it is cycled to a formable point, and with time at temperature, portions of the organic chains are broken and it becomes more brittle. Commercial grade (tinted blue) has no limit on the number of thermal cycle exposures allowed during production or in later assemblies. Thicker plates are built up by fusing smaller thicknesses at elevated temperatures. The polycarbonate used in reference 1 was made up in this manner. In contrast, military grade (yellow) polycarbonate is available only "as cast" with no thermal cycles. It has the highest resistance to impact fracture.

F-16 canopy - The F-16 canopy, as shown in figure 1, reference 2, is drape-molded to produce a single piece, compound curvature shape. It is a three-layer laminate. The inboard, half-inch thick layer is polycarbonate, created from military grade flat stock. The 0.050-inch thick inner layer is polyurethane, which is used to bond the polycarbonate to an outer 1/8-inch thick layer of acrylic. The canopy is bolted to a metal frame for the aircraft assembly. The U.S. Air Force supplied 10 scrap canopies that were rejected following flight service. These canopies were manufactured by TEXSTAR PLASTICS of Grand Prairie, TX, and by Sierracin Corporation of Sylmar, CA. Surprisingly different properties were observed between the two manufacturing sources; the TEXSTAR canopy could be easily cut with a saber saw, while the Sierracin unit could not. The Sierracin material softened around the saw and "gummed" it up, which indicated that softening occurred at a significantly lower temperature. The final full-scale canopy fracture demonstrations were conducted with TEXSTAR units.

Explosive material and holder - The preliminary tests, described in references 1 and 2, employed a lead-sheathed, pentaerythritoltetranitrate (PETN) mild detonating cord. For the remaining tests, a plastic explosive (DuPont trade name "detasheet," containing PETN with nitrocellulose and a binder) was obtained from the inventory of the U.S. Navy. It was selected for use, because of its flexibility, both in sizing the quantity used and in conforming to compound curvature of canopies. It works like "Silly Putty," easily molded, and has sticky, cohesive/adhesive properties. The material was installed in grooves cut in acrylic strips, which were in turn bonded to the test specimens. The explosive cords and holders were bonded into place, using transparent Dow Corning room temperature vulcanizing silicone compound (RTV) 3145. The explosive quantity was established by the size of the groove. The acrylic holder replaced a similar area removed from the canopy's outer acrylic layer within the moldline. Note: these explosive materials were used for the experimental development, but are not recommended for this application, due to a relatively low melting point and thermal stability. Other, more stable materials are available.

Explosive pattern - As shown in figure 2, the layout (grooves) for the explosive severance pattern for the first full-scale test was on the top centerline, forward and aft of crewmember, and around the lower extremity. The goal was to create a "French-door" opening. The initiation sites (2 for redundancy) were located at aft hinge points, which also is the closest access between the canopy and aircraft with the canopy open. On initiation, the explosive propagates upward and forward from these sites at a velocity of 22,000 feet/second. Common initiation points at intersections must be used to assure that the explosive propagation fronts remain in parallel to maintain shock wave augmentation for long-length applications.

FULL-SCALE TEST DEVELOPMENT PROCEDURE

The development proceeded from small plates to panels to the full-scale canopy.

Small plates - References 1 and 2 describe tests on small (6 X 6-inch) plates cut from commercial and military grade polycarbonate stock, as well as from F-16 canopies. The plates were tested with two edges clamped to simulate conditions within the canopy.

Panels - The same references also describe "mini-panel" tests with which experiments were conducted to determine the performance of the "French-door" severance pattern and of crack propagation. Explosive patterns were placed close to the edges of the panel. Additional mini-panel tests were conducted in which the panel was framed by 1/8th-inch skin thickness aluminum to simulate the stiffness afforded by the aircraft installation. Also, tests were conducted where the explosive patterns were placed well away from the edge of the panel.

Full-scale tests - All three tests were documented with high-speed video cameras.

The first test, as described in reference 2, used 2 lead-sheathed explosive cords that were placed in grooves cut into the exterior layer of acrylic in the pattern shown in figure 1. The cords were bonded into place with RTV-3145. The canopy was placed, unsupported, on a flat surface as shown in the figure. The ambient temperature was approximately 75° F.

The second test was conducted with two grooves cut into separate acrylic strips, filled with plastic explosive, and installed into slots from which the acrylic was removed from the canopy. The strips were bonded to the canopy using RTV-3145. Prior to installation of these strips, the 0.050-inch thick polyurethane middle layer was cut with a razor blade to negate its post-fire residual strength. Modified explosive patterns were used at the intersection sites of the severance paths. The objective was to independently sever these sites to allow end-to-end crack propagation. Again the canopy was unsupported on a flat surface. The ambient temperature was approximately 90° F.

The third full-scale test, figure 3, was conducted with a three-cord configuration of plastic explosive in acrylic strips and modified intersection charges. (Note: These intersection charges have been masked to meet ITAR regulations.) Prior to installation of these strips, using RTV-3145 as a bonding agent, the 0.050-inch thick polyurethane middle layer was cut with a razor blade to negate its post-fire residual strength. To simulate the aircraft installation, the canopy was fastened to a rigid frame. The canopy was attached to wooden beams that were contoured to fit the interior of the canopy-mounting interface. The beams were then fastened to a sheet of 3/4-inch plywood. The test was conducted at approximately 85 degrees.

TEST RESULTS

Small plates - The small-plate tests (references 1 and 2 and figure 1) revealed that the commercial grade polycarbonate in thicknesses to 1 inch were easily fractured with the two-cord explosive arrangement. However, the same test configurations had little effect on military grade material. A 0.063-inch thickness layer of polyurethane, between the explosive and polycarbonate, was required to efficiently couple explosive shock waves to sever a 0.9-inch thickness, military grade plate. In all small-plate tests (F-16 and military grade plate stock), this polyurethane inner-layer remained completely intact after the explosive firing.

Panels - The mini-panel tests were much simpler and less expensive than full-scale tests. The tests conducted with both lead-sheathed explosive cords, references 1 and 2, and subsequently with plastic explosive in acrylic holders, exhibited completely successful explosive propagation. The panel tests were somewhat misleading. The small, relatively flat panels were able to flex inboard on the desired cutting planes to provide an additional tensile force on the interior surface. Also, since the explosive patterns were close to the edges of the panels, internally initiated cracks easily propagated across the panel. However, subsequent tests with an aluminum frame and highly curved sections, which stiffened the panel, and with the explosive patterns placed at least 6 inches from the edge of the panel, complete severance could not be achieved. Tests with additional charges at the pattern intersections "punched out" those sites. Tests on highly contoured, stiff canopy sections, with a 3-cord explosive pattern and with the ends of the pattern free, achieved complete severance. Finally, it was observed that the 0.050-inch thick polyurethane middle layer, which remained completely intact after the explosive firing had considerable residual strength.

Full-scale tests - The assembly of the explosive into the canopy in all three tests was completely successful. No explosive propagation failures occurred. These tests also demonstrated that the acrylic strips could replace the outer layer of protective acrylic in the canopy installation.

In the first test (reference 2), approximately 9% of the parent strength remained in lengths between pattern intersections. However, no fractures occurred at the intersections. Since the parallel-cord configuration could not be maintained at these sites, the shock waves could not augment and severance could not occur. The canopy was effectively held together by these sites. Considerable deflection was observed as the explosive impulse pressed the canopy downward, and the unsupported sides on the flat surface slid outward.

In the second test, the additional charges in the intersections "punched out" those sites and assisted fracture. Total severance was observed across the aft transfer path, but, again, the residual strength of the running lengths, particularly the top/centerline path, remained too high. Similar deflections to those in the first test were observed.

The results of the third full-scale test (figures 4 and 5) left the canopy essentially intact, as had been observed in the first two tests. Little deflection was observed in the high-speed video. The intersections had been punched out, and the aft transverse path was totally severed, as observed in the previous test. A major, totally severed crack occurred diagonally across the right-hand panel, figure 5. This piece was easily pulled out by hand, figure 6, as were the remaining portions, as shown in figure 7. Complete severance occurred on every fracture line.

CONCLUSIONS

This paper describes a successful development of a unique 3-parallel-cord, augmented shock wave approach to explosively fracture a tough, polycarbonate F-16 aircraft canopy to allow through-canopy crew egress. A variety of lessons were learned in material evaluations, small-scale and mini-panel tests, and full-scale system tests.

Polycarbonate has a thermal memory that must be recognized and controlled. To maintain high strength and fracture resistance of military grade material, thermal elevations to significant softening point levels must be minimized. That is, to assure repeatable explosive fracture properties, processes to create canopies into final shape must be consistent.

Small-scale and mini-panel tests revealed that it's a long way from testing small pieces to a full-scale test. Tests on full-scale canopies, which are much stiffer and which require greater distances of the explosive patterns to the edge of the canopy, exhibited much higher resistance to fracture. Special patterns (not presented here, due to ITAR regulations) had to be developed to both maintain explosive propagation and punch out the intersections of fracture paths.

All objectives of the effort were met. The explosive materials can be installed on the exterior of the canopy within the mold line. The 3-cord explosive pattern is less visually obstructive than the pattern employed by the Harrier. Installing the explosive on the exterior eliminates inboard explosive debris or explosive pressure. The fractured canopy material beneath explosive intersections can be managed by positioning the intersections outside the crew envelope, or by structural containment. Explosive fracture is complete in less than 10 milliseconds; the explosive materials have detonated completely in less than 1 millisecond. The canopy maintains its shape after functioning, thus preventing major pieces from entering the cockpit. The residual strength of the fractured canopy is small; the seat can easily thrust aside the severed pieces of the canopy during egress.

The incorporation of this technology into future crew-escape applications offers a variety of improvements over canopy jettison systems. Heavier, stronger canopies can be used. Reducing delay times for canopy jettison can expand crew escape envelopes. System reliability can be increased; this is a passive system that has no mechanical interfaces that can improperly function, and fewer initiation inputs (2 for redundancy) are required. Canopy jettison systems require one or two latches, each with a release device, and two thrusters or rockets, totaling 6 to

8 inputs. Canopy fracture should weigh and cost less. It should have lower maintenance costs. It will be a single, one-time installation of explosive material, which will last the lifetime of the canopy

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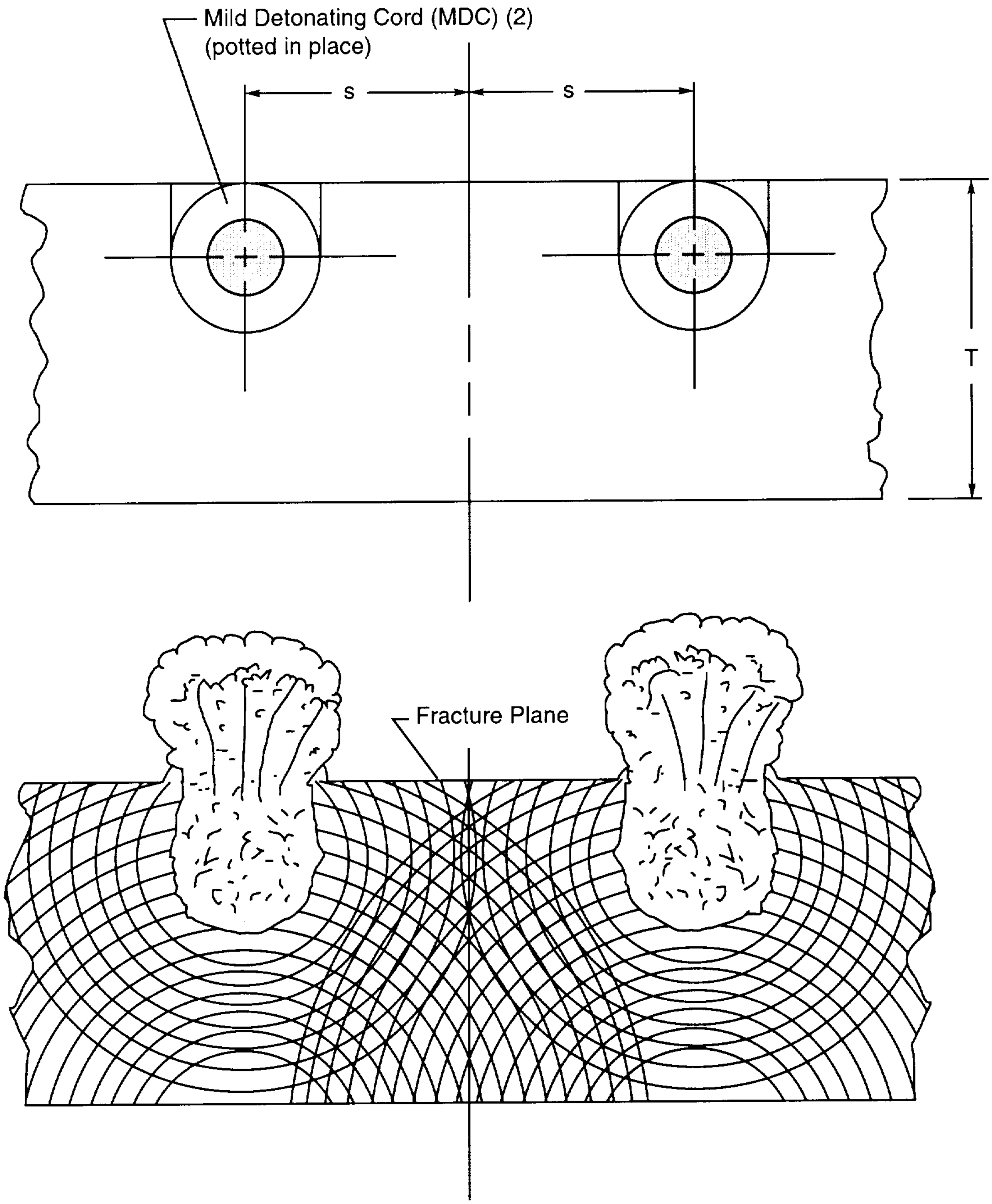

Figure 1. Cross sectional view of augmented shock wave severance principle.

Figure 2. Concept for explosive fracture of F-16 aircraft canopy to allow through-canopy crew egress.

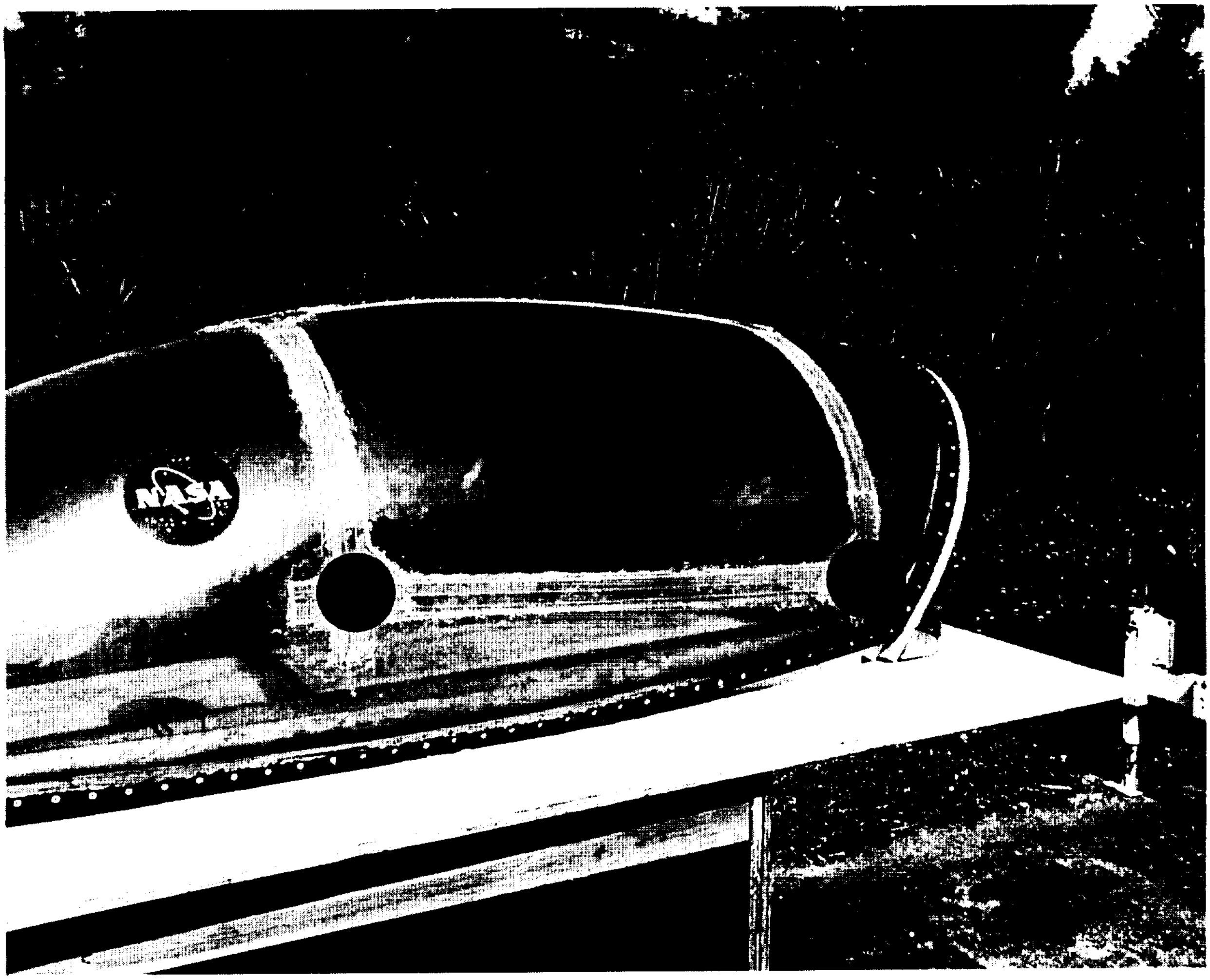

Figure 3. Test setup for third full-scale canopy test. (Explosive intersections have been blanked to accommodate ITAR restrictions.)

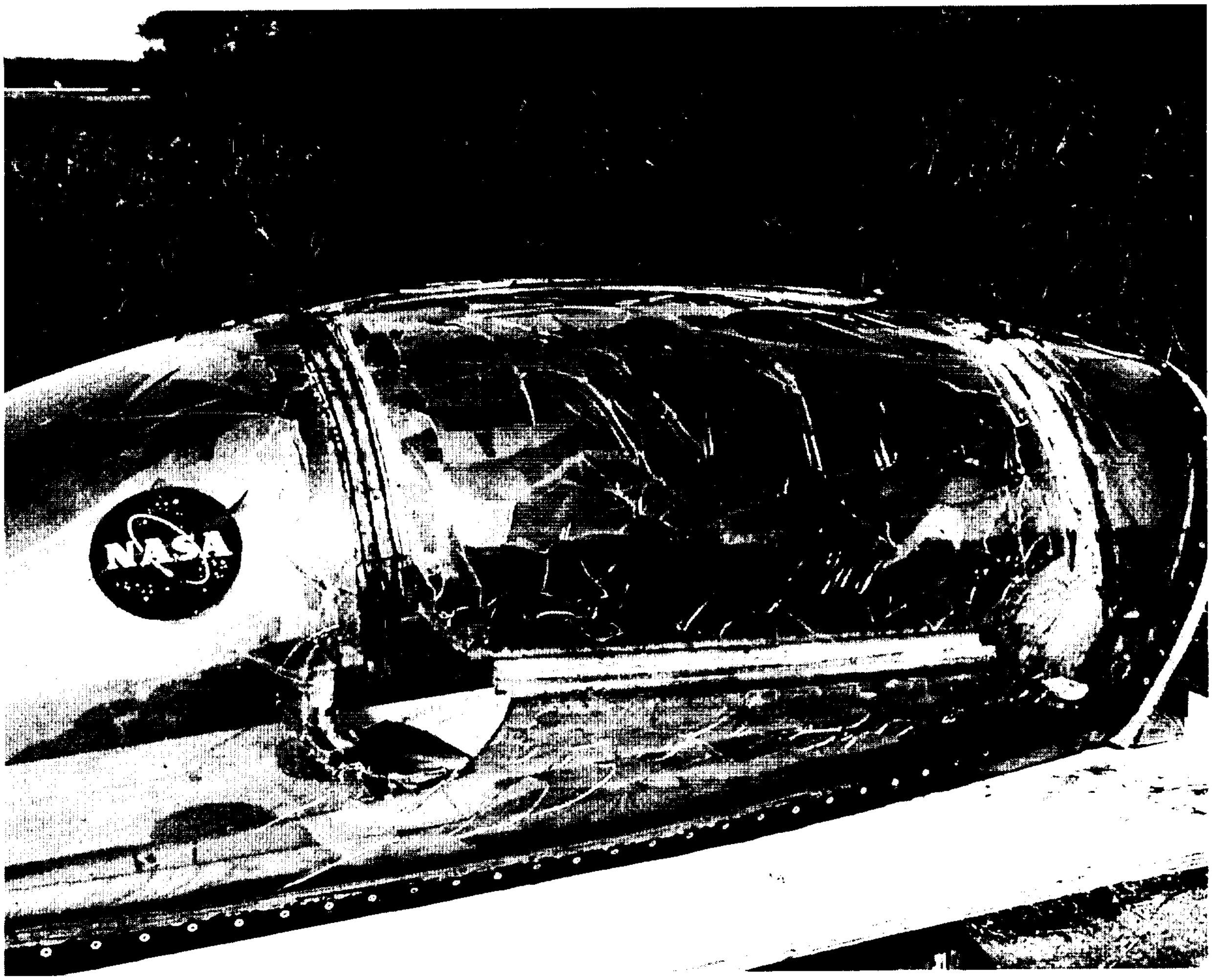

Figure 4. Results of the third full-scale canopy test, side view.

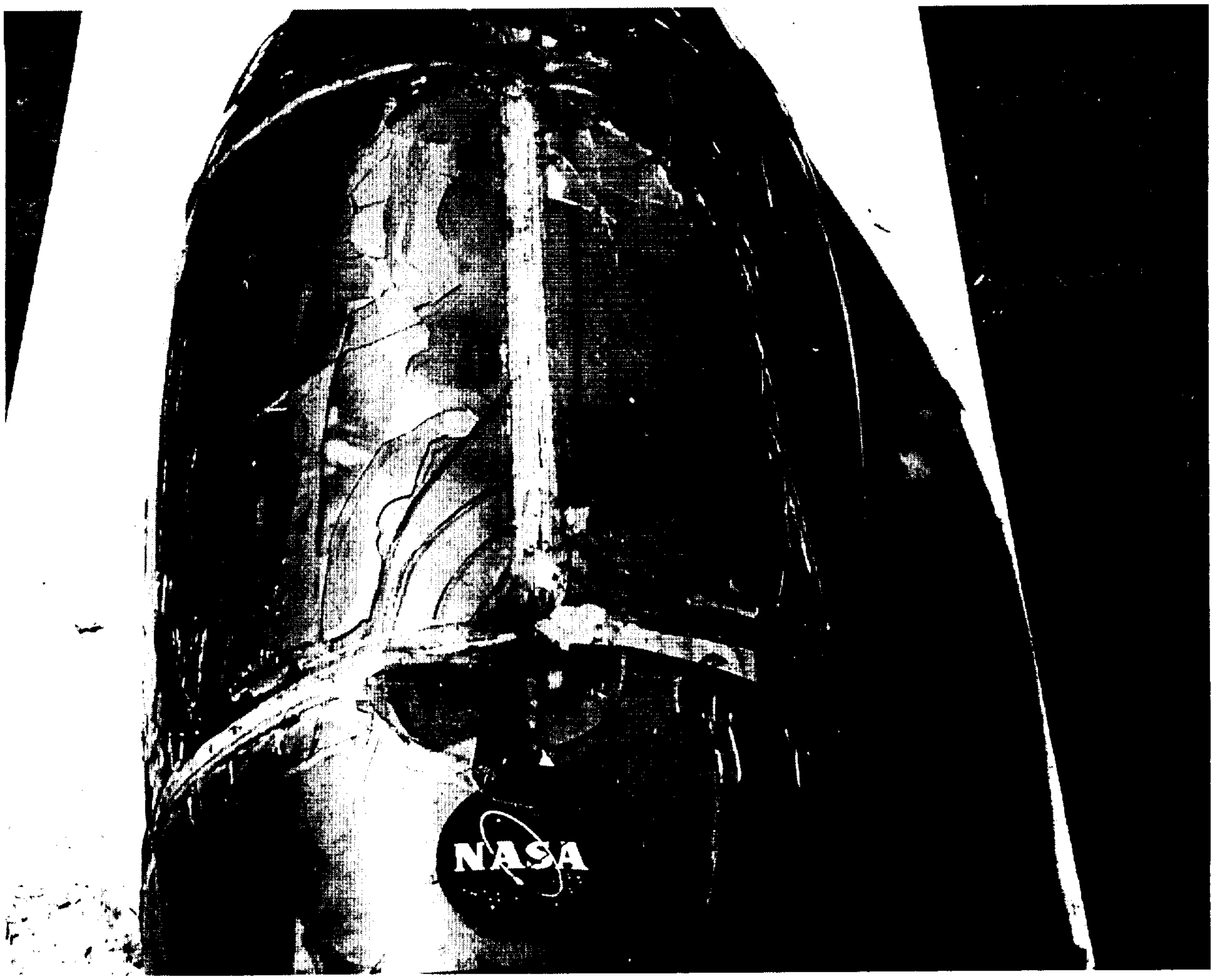

Figure 5. Results of the third full-scale canopy test, top view.

Figure 6. Manually removing the severed panels in the third full-scale canopy test.

Figure 7. Final results of the third full-scale canopy test.