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Investigation of Super*Zip Separation Joint

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Preface

Following the second failure of a Shuttle/Centaur Lockheed Super*Zip separation joint in a thermal evaluation test program in March 1984, a performance investigation was initiated in June 1984 at the NASA Langley Research Center. A committee made up of representatives from Government and industry was created to manage the investigation in terms of real-time test planning, data analysis, and recommendations for system design and quality improvements. The program director was Norman R. Schulze from the Office of the Chief Engineer at NASA Headquarters. The program manager was the author, Langley's Pyrotechnic Support Engineer. The organizations participating in the committee were as follows:

NASA Headquarters

NASA Lewis Research Center

NASA Johnson Space Center

NASA Marshall Space Flight Center

NASA Langley Research Center

Jet Propulsion Laboratory

Air Force Systems Command, Space Division

Naval Strategic Systems Project Office

Lockheed Missiles & Space Co., Space Division

Lockheed Missiles & Space Co., Trident Division

Boeing Aerospace Co.

General Dynamics Corp., Convair Division

The Aerospace Corp.

The Shuttle/Centaur propulsion system has been abandoned since this work was completed in 1986, based on a concern for the risk of hydrogen fuel entrapment within the Shuttle cargo bay.

Summary

Following functional failures of two of five Lockheed Super*Zip spacecraft separation joints in a development test series to quantify thermal effects, an investigation program was initiated on this and related systems to assist in preventing recurrence of failure. The Super*Zip joint, applied in a ring configuration, utilizes an explosively expanded tube to fracture surrounding prenotched aluminum plates to achieve planar separation. A unique test method was developed and more than 300 individual test firings were conducted to provide an understanding of the severance mechanisms, the functional performance effects of system variables, and the most likely cause of system failure. An approach for defining functional margin was developed, and specific recommendations were made for improving existing and future systems.

Introduction

The patented Lockheed Super*Zip spacecraft separation joint was planned for use on the Space Shuttle to release the Centaur vehicle (120-in. diameter), the Inertial Upper Stage (IUS) (91 in. at the same separation plane as the Centaur), and the Galileo spacecraft (55 in. in the separation plane shown). (See fig. 1.) Figure 2 shows cross sections of the cylindrical structures that achieve separation. The IUS joint has the same configuration as the Centaur joint, except for the outer structure. A number of components are dissimilar between the joints. Figure 3 identifies the components used throughout this paper. Separation is accomplished when either explosive cord is fired. The explosive pressure wave expands the tube (which contains all explosive products) against the doublers and fractures are induced in the ligaments progressing around the cylinder. The doublers are overlapping aluminum plates (metal grain, or roll, direction down the length), positioned as shown in figure 4 for the Galileo separation joint, which has 27 doublers.

Following functional failures of two of a group of five Lockheed Super*Zip spacecraft separation joints in a Shuttle/Centaur thermal development test series to quantify thermal effects, an evaluation program was initiated on this and the related IUS and Galileo systems to assist in preventing a recurrence of failure. The conditions of the test failures and early observations follow. The explosive loads for all tests ranged from 8.77 to 9.14 grains/ft. The five joints were residual hardware obtained from a previous program which required a 79-in.-diameter joint rather than the 120-in.-diameter joint required by the Centaur. These joints were among the earliest manufactured with 7075-T73 aluminum. The original designs of the aluminum Super*Zip joints utilized 7075-T6 aluminum. The change had been made to avoid stress corrosion sensitivity. A series of five thermal development tests were conducted, one at approximately −40°F, three at −80°F, and one at −120°F. The failures occurred at −80°F and −120°F. The joints were cooled in a closed chamber, free from moisture or frost buildup. The thicknesses of doublers in all five tests (39 doublers per test) are summarized in table I. Functional failures (i.e., no severance) began occurring at a thickness of 0.086 in., and as thickness increased more failures occurred, even though all ligaments were closely controlled to ±0.002 in.

A research program was initiated on the Shuttle/Centaur and Galileo separation joints with the purpose of determining the most likely cause of the failure and recommending improvements. The specific goals were as follows:

1. Understand the severance mechanisms.
2. Develop test methods to evaluate severance.
3. Determine functional performance effects of system variables.
4. Determine functional margin.

More than 300 individual test firings were conducted in meeting these goals.

Test Apparatus

This section provides details on the Super*Zip joint components and the supporting test hardware.

Explosive Loads

The explosive loads used in this program are shown in figure 5. The Super*Zip systems use cyclotetramethylenetetranitramine (HMX) as the explosive (top sketch), and this was also used in the evaluation tests unless otherwise noted. All Super*Zip cords were manufactured to achieve the final 0.125-in. diameter for all explosive loads; the lead wall thickness was adjusted, thicker for smaller explosive loads and thinner for larger explosive loads. The velocity of explosive propagation for HMX is approximately 23 000 ft/sec. The remaining explosive cords used are shown in lower sketches. Cyclotrimethylenetrinitramine (RDX) and HMX have equivalent output performance.

Steel tube

The tube shown in figure 3 was 347 corrosion-resistant steel (see MIL-T-8808B), with no annealing after shaping. The grain size was ASTM 7 or finer. (See ASTM Methods E 112 for Estimating the Average Grain Size of Metals.) The wall thickness was 0.035 + 0.001/−0.003 in. with a weight of 0.240 lb/ft. Dimensionally, the major axis was 0.83 ± 0.02 in. with a 0.50-in. flat, and the minor axis was 0.285 ± 0.010 in.

Extrusion

The Super*Zip extrusions were silicone rubber with a Shore hardness of A55 and with a powdered Dupont Teflon coating. The major axis dimensions were 0.730 ± 0.010 in. and the minor axis was 0.190 ± 0.010 in. No dimensional controls were applied to the dimensions of the flat and protrusions.

Standard Tapered-Plate Test Joint

Figure 6 shows the tapered-plate test joint used to compare the performance of different test parameters. The fasteners were aircraft-quality nuts and bolts rated to withstand 125 000 psi of pressure. The entire assembly was suspended by wires attached to the fasteners to avoid introducing external forces. The principle in using the tapered plate is that the bending resistance increases with increasing thickness to stop fracture of the plate within a short length. To determine the terminus of the fracture in the ligament, talcum powder was dusted over the top of the plate and pressurized air was applied from the bottom through the fracture. The point at which the talcum was undisturbed indicated the terminus. The thicknesses of the plate and of the ligament at the fracture terminus were recorded in each test. The thickness and length of the tapered plate were designed to accommodate the full range of inputs from the various test combinations. The advantage of this test method is that the maximum severance capability for any particular set of test parameters can be measured in each test. Five tests were normally conducted with each configuration to determine an average and standard deviation for each set of 10 tapered plates. The velocity of explosive propagation down the length of the cord was measured (with method described in ref. 1) in each test to assure performance uniformity.

Rigid Test Fixture

The steel fixture shown in figure 7 provided a method of simulating extremely rigid interfaces to the separation joint. Test joints were bolted to the fixture with 0.25-in. bolts on 1.50-in. centers.

High-Fidelity Panel

An accurate representation of a section of the 120-in.-diameter Shuttle/Centaur Super*Zip separation joint is shown in figure 8. The 26-in. length of doublers contained one full-length doubler on both the outboard and inboard surfaces with shortened doublers on each end of the full-length doublers. The 7075-T73 doublers were 0.082 in. thick (0.042-in. ligament) with a Rockwell hardness of B78, yield strength of approximately 54 600 psi, and an ultimate strength of approximately 65 100 psi. Hi-Lok[1] fasteners were used at the exact hole spacing, including plate-to-hole edge distances. Two sets of end ring assemblies were used. The doublers were shaped separately and drilled in a specially designed holding fixture.

Test of 120-In.-Diameter Ring

Two complete 120-in.-diameter ring sets were mated to represent flight structural interfaces with

[1] Hi-Lok: trademark of Hi-Shear Corp.

the joint, as shown in figure 9. The 26-in. high-fidelity doublers were mounted on the rings using existing holes. Opposite the doublers an "H" block (see arrow in fig. 9) was mounted to hold the rings at the correct placement and to allow the rings to open like a clamshell on firing of the Super*Zip section. The rings were lashed together at the 90° and 270° quadrants with parachute cord, and the rings were held apart by rectangular spacers. The parachute cords were severed with pyrotechnic cutters, which were fired at the same time as the Super*Zip section to minimize structural distortion at the time of severance. Additional slack cords allowed the lower ring to drop 1 in. once the rings were separated. The rings were hung at four quadrants to assure recognition of any force inputs on activation. Cameras operating at 24 and 400 frames per second were used to monitor the test.

Test Procedures

The test program, which required high levels of quality control, was divided into four major areas: development of comparison test method, evaluation of variables, correlation of tapered-plate data to flight-hardware data, and determination of functional margin.

Quality Control

All aspects of material preparation were closely controlled, followed by a thorough inspection and recording of all hardware used. Each piece of hardware was serialized.

Heat-treating was accomplished in forced-air ovens (controlled to a maximum tolerance of 4°) on specimens no larger than 3 by 30 in. All specimens were separated, never stacked, to assure uniform exposure. Hardness readings were taken every 2 in. with calibrated Rockwell machines and averaged for the specimen. Conductivity measurements were made on each piece, with the entire length being scanned.

Hardness readings were made on each manufacturer's lot of rubber extrusions. Dimensional inspections and records were made at 1-in. intervals on each length of extrusion.

Dimensional inspections and records were made on each machined tapered plate at each intersection of a 0.5-in. grid (including the notches), a total of 51 measurements for the 8-in. plates.

Constant-thickness plates for high-fidelity tests were individually rolled in 3-in.-wide strips from 7075-T6 mill stock aluminum prior to heat-treating. Thicknesses were controlled to +0/−0.001 in.

A holding jig was designed to drill the 70 holes through each of the 6 plates for the high-fidelity tests. The plate sets were entirely interchangeable.

Each Hi-Lok fastener was dimensionally checked for the diameter of the shank, bolt head, and nut. The shank dimensions had less than 0.001 in. variation. The bolt heads and nuts were held to a 0.005-in. tolerance.

The explosive load was checked through use of a washout technique and was recorded at intervals of 3 to 5 ft for each length of explosive.

Each tube was weighed and dimensionally checked, including an ultrasonic scan of the wall thicknesses of both flats and of both peak radii.

The velocity of explosive propagation was measured in each test to assure reproducibility of explosive performance.

Development of Comparison Test Method

Test methods had to be developed to evaluate and compare the effects on severance of various test parameters and conditions. Requirements would be accuracy, reproducibility, and low cost, since a statistical approach is necessary for these single-shot devices. The best comparisons would be made when the maximum severance performance could be determined for each set of test parameters and conditions. A test method that incorporated all these features and could measure the maximum severance capability in each firing would be ideal.

Past experience (ref. 1) showed the advantage of tapered plates, which provided a starting point for development of a "maximum severance" measurement test. Several tapered interface configurations were evaluated: constant-thickness plates (webs) with tapered ligaments, tapered plates (webs) with constant-thickness ligaments, and tapered plates (webs) with tapered ligaments. A 0.060-in.-ball end mill was used to cut notches. The explosive loads used for these tests ranged from 8.5 to 9.0 grains/ft. The single-cord configuration was used initially.

Constant-thickness plates with tapered ligaments. Plate thicknesses of 0.106, 0.086, and 0.081 in. with ligaments tapering from 0.015 in. up to runout in the 11-in. length were tested.

Tapered plates with constant-thickness ligaments. Plates 11 in. long and tapering from 0.123 to 0.043 in. with ligaments of 0.023, 0.044, and 0.063 in. were tested. Five units were tested in each configuration.

Tapered plates with tapered ligaments. Plates 11 in. long and tapering from 0.123 to 0.043 in. with ligaments tapering from 0.095 to 0.015 in. were evaluated. Dual-cord configuration tests were then initiated, decreasing the plate lengths to 9.5 and

8.0 in. The same plate and ligament tapers as those for the 11-in. length were maintained. That is, for the 8-in. length, the plate tapered from 0.123 to 0.065 in. and the ligament tapered from 0.095 to 0.037 in. (fig. 6).

Flat-plate validation. A series of tests were conducted to determine if the data produced by the tapered plates with tapered ligaments could be related to performance in constant-thickness plates with constant-thickness ligaments. Constant-thickness plates were tested at the thicknesses indicated by the tapered-plate tests. A rectangular explosive cord with an explosive load of 20 grains/ft and encased in shrink tubing to prevent fragmentation (fig. 5) was used, the cord being centered in the tube with low-density foam. Test plates 5.3 in. in length were machined to web and ligament thicknesses through the range of thicknesses severed by the tapered-plate test configuration.

Flare measurement comparison method. In an effort to obtain some information on the amount of excess energy beyond that necessary to achieve severance of constant-thickness plates with constant-thickness ligaments, measurements were made on the amount of bending of the severance plane achieved by the fractured plates. The measurement was made across the top and bottom halves of the severed doublers. The top explosive, or the cord closest to the spacecraft side of the joint, was the first to be fired in the normal separation sequence.

Evaluation of Variables

A total of 18 variables were evaluated. These variables are listed below and are discussed in the following sections:

1. Structural properties of doublers
2. Thickness of doubler
3. Thickness of ligament
4. Explosive load
5. Explosive shape
6. Explosive location
7. Bolt hole location
8. Notch-to-fastener length
9. Wall thickness of tube
10. Free volume inside tube
11. Free volume between tube and doublers
12. Notch shape
13. Structural mass and stiffness of end plates
14. Doubler preload
15. Vacuum environment
16. Length of doublers and gaps between doublers
17. Fastener strength
18. Cold temperatures

Structural properties of doublers. Heat-treatment, or accelerated aging, experiments were conducted on 7075-T6 to determine the variations possible in achieving the 7075-T73 condition. The heat-treatment standard MIL-H-6088F states that to obtain 7075-T73, expose 7075-T6 to heats of 315°F to 335°F for 24 to 30 hours, with a minimal allowable Rockwell hardness being B77 and a minimum allowable conductivity being 38 percent. Specimens of 7075-T6 were exposed to the following combinations: 315°F for 24 hours, 335°F for 30 hours, 325°F for 24 hours, and 325°F for 27 hours. Classic dog-bone pull tests were conducted on samples of each of these specimens to determine maximum stress and elongation properties. Test firings of 7075-T6 tapered-plate specimens, as shown in figure 6, were conducted and compared with those produced with 7075-T73 for an explosive load of 9 grains/ft.

Thicknesses of doublers and ligaments. The Galileo severance joint, the left sketch in figure 2, was evaluated for a representative tapered plate with a reduced web and constant-thickness ligament. Explosive loads of 7.0 and 11.2 grains/ft were evaluated.

Explosive load, location, and shape. Explosive load versus severance performance was compiled for the standard test configuration (fig. 6). Explosive loads of 7.6, 9.0, and 11.0 grains/ft were tested in both the dual- and single-cord configurations. Also measured (with the crushable-honeycomb method described in ref. 1) was the energy delivered by the tube. The performance of a 2-in. length of tube was measured, and to assure that only that output was measured, the tube was clamped on either side of the length measured. This energy was compared with the impact against the joint from a 5-lb mass dropped from various heights. The impacting interfaces were the original and expanded shapes of the tube.

As a physical limit for explosive load and shape, a ribbon explosive with an explosive load of 20 grains/ft (fig. 5) was evaluated. The ribbon explosive was encased in two layers of plastic tape to reduce fragmentation and was centered in the tube with low-density foam.

Bolt hole location. To evaluate the effect of bolt hole location, fasteners with different "footprints," or bolt head and nut diameters, were tested. These footprints had the effect of widening and narrowing the moment arm over which bending occurred in the doubler plates or moving the bolt holes with a single footprint diameter. The footprint of the washers for the standard test configuration (fig. 6) was 0.312 in. For the Hi-Lok fastener, the diameter for the bolt head was 0.365 in. and for the nut was 0.306 in.

Free volume internal to tube. Two test series were conducted to determine the effect of limit conditions on tapered-plate severance. The first series was conducted by completely filling the tube with room-temperature-vulcanizing (RTV) silicone compound. General Electric RTV 560 compound was used. The second series utilized the maximum free volume between the centered explosive cord and the tube. The explosive loads were combinations of the explosive cords shown in the lower portion of figure 5. These configurations were compared with the single-cord configuration Super*Zip extrusion. Also, a test series for a dual-cord configuration with a standard tapered plate was made in which the extrusion was stretched to increase the internal free volume by 21 percent.

Free volume external to tube. Two test series with the standard tapered plate were conducted with an introduction of a 0.020-in. gap between one doubler and the tube. The first test had only air in the gap, and the second test had the entire volume around the tube and between the tube, end plates, and doublers filled with RTV 102 compound.

Tube containment. Cross-sectional cuts were made at several locations in tubes used in tests with different explosive loads and explosive locations to determine the cause of ruptures observed with higher explosive loads. Also, as a limit evaluation, two cords with an explosive load of 8.5 grains/ft were fired simultaneously.

Notch shape. Tests with tapered plates were conducted on 0.250- and 0.030-in.-diameter end-milled grooves to compare with the 0.060-in.-diameter grooves. The tapered plates and the depth of the grooves were the same in all tests.

Structural mass and stiffness. To determine the influence of the mass and stiffness of the end rings and surrounding structures, the end plates were changed from aluminum to steel and a rigid fixture was used. The 1.7- by 11.0-in. aluminum end plates of the standard tapered-plate test configuration were replaced with 3.0- by 11.0-in. steel plates. The rigid fixture, which fixed the relative position of the standard end plates, is shown in figure 7. The standard tapered-plate test configuration was used and explosive loads of 9 grains/ft were used for all tests. A moment of inertia structural analysis was made on the Shuttle/Centaur flight structure to determine if it could be influenced by the bending of the doublers at severance. The analysis was limited to the area 1 in. beyond the bolted interface of the flanges of the end rings. (See fig. 2.)

Fastener strength. A group of five test firings at an explosive load of 9 grains/ft were conducted with nuts and bolts having strengths of 65 000 psi to compare with the performance of the standard nuts and bolts having a strength of 125 000 psi.

Doubler preload. Three tests were conducted in which the tube was loaded perpendicular to the flat plane of the standard tapered-plate test configuration. The test configuration was supported horizontally by cables attached to the fasteners at each end of the assembly and 20-, 50-, and 100-lb weights were hung by cables across each end of the tube projecting from the assembly.

Vacuum. Five tests using the standard tapered-plate test configuration were conducted in a vacuum of 5×10^{-6} torr.

Cold temperatures. Tests with the standard tapered-plate test configuration were conducted at −20°F, −40°F, −60°F, −80°F, −120°F, −160°F, and −200°F. The tapered-plate assembly was hung vertically by cables attached to the top fastener pair in a vertical, covered, 10-in.-diameter cylinder that was flooded with cold nitrogen gas. The gas flow was regulated to establish the desired temperature. Each specimen was stabilized 15 minutes before firing. Also, each specimen had the tube ends plugged with modeling clay, and each end of the extrusion was clamped to allow for stretching due to shrinkage. High-fidelity test firings (fig. 8) were conducted with an explosive load of 7.6 grains/ft at −30°F and −35°F. Tests with loads of 7.5 to 7.6 grains/ft were conducted at −120°F, and a test with a load of 9.0 grains/ft was conducted at −65°F. These specimens were hung horizontally, and post-test flare measurements were taken.

Correlation of Tapered-Plate Data to Flight-Hardware Data

The culmination of this test evaluation program was to correlate the data collected from the standard tapered-plate configuration to data from flight hardware. This correlation would allow designers to more accurately accommodate system variables in future systems. Since the standard tapered-plate test configuration measures the maximum severance performance for each set of conditions, establishing the maximum severance capability with flight hardware would provide the correlation. Recognizing that the ligament thickness for flight hardware could be more easily controlled than mill run sheet stock, we fixed the ligament thickness at 0.042 ± 0.002 in.

and increased the doubler plate thickness. Incrementally increasing flat plates, 11 in. in length with 0.042-in. ligaments, were used to establish the thickness that could be fractured in the flight configuration. The amount of flare (dimension of post-test doubler bend) was measured in each test to assist in this measurement.

Determination of Functional Margin

Since no generally accepted guidelines exist for demonstration of the functional margin of this type of separation joint, an effort was made to develop a standard. This standard would have to recognize the sensitivity of the variables within the system. Once the variable sensitivities were established, the margin was determined by analysis, by testing, and by a combination of the two. The challenge was to determine and compare the critical variables that can be modified to meet flight requirements.

Results

The results of this effort are described under the same headings as the Test Procedures section: development of comparison test method, evaluation of variables, correlation of tapered-plate data to flight-hardware data, and determination of functional margin.

Development of Comparison Test Method

Several test configurations were evaluated, including flat and tapered plates and ligaments.

Constant-thickness plates with tapered ligaments. The results of the test series for constant-thickness plates with tapered ligaments are summarized in table II. At the plate thickness of 0.106 in., only superficial cracks appeared on the surface at the bottom of the notch. These cracks only occurred in the ligament thicknesses from 0.040 to 0.100 in. Fractures began occurring in plate thicknesses of 0.086 in. at the ends and in the center portion of the plate. However, at a plate thickness of 0.081 in., fractures occurred only in the middle of the plate, as shown in the sketch below table II.

Tapered plates with constant-thickness ligaments. For the plates tapering from 0.123 to 0.043 in., the tests with the 0.023-in. ligaments resulted in an average web thickness of 0.0983 in. with a standard deviation of 0.0054 in. However, the 0.044- and 0.063-in. ligaments yielded complete severance of the plate. For the 0.063-in. ligament, severance was achieved up to notch runout.

Tapered plates with tapered ligaments. The single-cord configuration of tapered plates with tapered ligaments severed to a 0.112-in. web with a 0.082-in. ligament. However, in tests of the dual-cord configuration, several of the plates failed to sever at the thin end of the plates. The same results occurred with 9-in. plates. The 8-in. plates (fig. 6) with the dual-cord configuration were all successful, producing the results (shown in table III) which were used as the performance standard. The performance of this configuration was used as the flight-load standard for all subsequent comparisons.

Flat-plate validation. The test series with the explosive load of 20 grains/ft, used as a basis to compare performance of tapered plates with that of flat plates, severed to a web thickness of 0.110 in. with a ligament thickness of 0.083 in. Flat plates of the following web/ligament thicknesses produced no severances: 0.140/0.114 in., 0.128/0.100 in., and 0.120/0.092 in. Partial severance occurred 2.0 in. in from each end of the 5.3-in. plates at 0.115/0.087 in. Complete severance occurred at 0.110/0.082 in. and at 0.095/0.067 in.

Evaluation of Variables

The results of the evaluation of the 18 variables are described individually in this section. At least five test firings were made for each variable.

Structural properties of doublers. The results of the investigation of accelerated aging of 7075-T6 aluminum are shown in table IV and the mechanical properties are shown in figure 10. As the temperature/time profile increased, the hardness and strength decreased and the conductivity increased, as expected. The elongation property dropped and recovered slightly. The functional performance of the 7075-T6 aluminum shown in table V (0.1396-in. web and 0.1117-in. ligament) was significantly better than the performance standard for the 7075-T73 material in table III (0.0899-in. web and 0.063-in. ligament). These data are plotted in figure 11.

Thicknesses of doublers and ligaments. The results of this evaluation were generated in the test method development. To summarize, thin (0.015 to 0.030 in.) ligaments did not sever. As the ligament thicknesses were increased (0.035 to 0.063 in. in tapered plates), severance occurred. Tapered test plates stopped severance within the 8.0-in. length of the configuration shown in figure 6.

The performance of the unique Galileo joint, with the 0.020-in. reduced cross section of the web, a constant 0.025-in. ligament, and an explosive load of 11.2 grains/ft, is summarized in table VI. The explosive load of 11.2 grains/ft severed an average web thickness of 0.121 in. with a standard deviation of 0.0037 in. For the load of 7 grains/ft, the average web thickness was 0.0876 in. with a standard deviation of 0.0043 in.

Explosive load, location, and shape. Figure 11 shows the results of the evaluation of explosive load and location for the tapered-plate test configuration. The lowest curve is for the dual-cord configuration performance, and the top curve is for the single-cord performance, a 17-percent increase. The energy delivered by the dual-cord configuration is presented in figure 12. The single-cord performance was comparable. No correlation in these energy values could be achieved with an impacting mass. No severances occurred for impacting masses with up to 1.48 times the energy produced during firings.

The centered ribbon explosive test series yielded an average web of 0.144-in. (standard deviation of 0.0046 in.) with a 0.115-in. ligament (standard deviation of 0.0046 in.).

Bolt hole location. The performance of the Hi-Lok fasteners is shown in table VII. The 0.365-in.-diameter bolt head footprint yielded an average web thickness of 0.086 in. at the fracture point, while the 0.306-in.-diameter nut yielded a web thickness of 0.0923 in. The 0.312-in. footprint for the standard test configuration (fig. 6) produced a web thickness of 0.0899 in. at the fracture.

Free volume internal to tube. The results of the investigation of the internal free volume are summarized in figure 13. The curve on the left, for minimum free volume, was obtained by fully potting the explosive cord in the tube. The center curve is the performance of the single-cord, standard-extrusion configuration, and the right curve is the performance delivered by the explosive cord centered by low-density foam. The evident data scatter was produced by the use of different-shaped explosive cords. (See fig. 5.) When the extrusion for the dual-cord configuration was stretched to reduce the volume by 21 percent, the average performance was a web of 0.0818 in. (standard deviation of 0.004 in.), as compared with the standard configuration (0.0899-in. web and 0.063-in. ligament).

Free volume external to tube. Introducing a 0.020-in. gap between the tube and one doubler produced an average web of 0.0863 in. (standard deviation of 0.0034 in.) and a ligament of 0.0567 in. (standard deviation of 0.0035 in.). However, completely filling this 0.020-in. void and the free volume at the tube radii with RTV compound increased the web to 0.1028 in. (standard deviation of 0.0021 in.) and the ligament to 0.077 in. (standard deviation of 0.0029 in.).

Tube containment. Photographic enlargements of tube cross sections at the site of tube ruptures are provided in figure 14. The internal tube wall has been roughened by the firing. The photograph on the left shows that the tensile failures initiated from the inside of the tube at the peak of the tube radii. Figure 15 shows typical post-test tube wall thicknesses for various test configurations and explosive loads. The simultaneous firing of two cords with an explosive load of 8.5 grains/ft did not produce a tube fracture.

Notch shape. Increasing the diameter of the notch from 0.060 to 0.250 in. resulted in no fracture of any tapered plate. Reducing the notch diameter to 0.030 in. produced no appreciable change in performance from that of the standard 0.060-in. notch.

Structural mass and stiffness. Structural stiffness was assessed by replacing aluminum with steel end plates. This produced an average web of 0.0999 in. (standard deviation of 0.0031 in.) and a ligament of 0.0714 in. (standard deviation of 0.0036 in.). The rigid fixture produced an average web of 0.0937 in. (standard deviation of 0.0026 in.) and a ligament of 0.0685 in. (standard deviation of 0.0028 in.). The moment of inertia analysis of the system provided the following results: upper ring—0.0642 in^4; lower ring—0.0535 in^4; upper structure 1 in. beyond the upper ring—0.0623 in^4; lower structure 1 in. beyond the lower ring—0.0517 in^4; undeformed doublers—0.0132 in^4; and deformed doublers—0.0161 in^4. The change in stiffness with use of the full-diameter end rings is described in the section entitled *Correlation of Tapered-Plate Data to Flight-Hardware Data.*

Fastener strength. Reducing the bolt strength from 125 000 to 65 000 psi produced no appreciable change in severance capability. The last two fastener pairs at the thick end of the tapered plate (well beyond the fracture termination point) did suffer thread deformation.

Doubler preload. The results of introducing side loads of 20, 50, and 100 lb are summarized in table VIII. Increasing the side load produced no appreciable improvement in severance performance compared with the performance standard of 0.0899-in. web and 0.063-in. ligament.

Vacuum. The performance of the test series fired under a vacuum of 5×10^{-6} torr was an average web of 0.093 in. (standard deviation of 0.0023 in.) and a ligament of 0.062 in. (standard deviation of 0.0024 in.).

Cold temperatures. The results of the tapered-plate test firings conducted over a wide range of cold temperatures are summarized in table IX. Table X shows the results of the high-fidelity test series at various test temperatures, with the exception of the test firing for an explosive load of 7.5 to 7.6 grains/ft at −120°F, which failed to completely sever. The end with the core load of 7.5 grains/ft did not sever, but the end with the core load of 7.6 grains/ft did sever. The velocity of explosive propagation for this series was approximately 23 000 ft/sec, the same as that at laboratory ambient temperature.

Correlation of Tapered-Plate Data to Flight-Hardware Data

The final tests to correlate the tapered-plate performance, relative to the performance produced with flight hardware, are summarized in table XI and plotted in figure 11. Complete severance was achieved in all tests. As the explosive load increased, the amount of post-test flare increased. A close-up end view of a typical joint half illustrating post-test flare is shown in figure 16. Furthermore, as the maximum-thickness severance capability for each explosive load was approached, the difference in flare between the top and the bottom assemblies decreased. This information is corroborated by the results from table X.

The full-diameter ring test produced an average flare on the top doubler half of 0.734 in. with a standard deviation of 0.009 in.; on the bottom the flare was 0.803 in. with a standard deviation of 0.007 in. These values were virtually the same as the equivalent segment results of test 176 in table X (0.721 in. for the top and 0.801 in. for the bottom).

Determination of Functional Margin

To consider functional margin, the influential parameters of this system that most affect design are explosive load and doubler (web) thickness. All margin considerations should be based on the worst-case conditions of hardware and environment.

For explosive load, the functional margin would be a ratio of minimum available flight load to the minimum explosive load required to break the thickest doubler (web) possible:

$$\text{Explosive margin} = \frac{\text{Minimum flight load}}{\text{Minimum load to break thickest doubler}}$$

For doubler thickness, a structural analysis for cantilevered beam deflection (because deflection is necessary to achieve fracture) is

$$\delta = \frac{FL^3}{3\epsilon I}$$

which yields

$$F = \frac{3\epsilon I\delta}{L^3}$$

where

δ	beam deflection at notch
L	length of beam
F	force required to deflect beam
ϵ	Young's modulus
I	moment of inertia, $WT^3/12$
W	width of beam
T	thickness of beam

For energy E to bend the beam,

$$E = \frac{F\delta}{2} = \frac{3\epsilon I\delta^2}{2L^3} = \frac{3\epsilon\delta^2(WT^3/12)}{2L^3}$$

For constant deflection, E is proportional to T^3. Therefore, to establish a functional margin related to doubler thickness,

$$\text{Doubler margin (minimum flight explosive load)} = \left(\frac{\text{Minimum thickness severed}}{\text{Maximum allowable thickness}}\right)^3$$

For the Shuttle/Centaur separation joint at a minimum load of 9.5 grains/ft,

$$\text{Explosive margin} = \frac{9.5 \text{ minimum load}}{7.5 \text{ minimum load to break}} = 1.27$$

The value 7.5 grains/ft for minimum load to break was obtained from the high-fidelity test series, which is plotted in figure 11. The doubler margin is as follows:

$$\text{Doubler margin} = \left(\frac{0.098 \text{ minimum severed thickness}}{0.082 \text{ maximum allowable thickness}}\right)^3 = 1.71$$

The 0.098-in. thickness at minimum explosive load of 9.5 grains/ft was interpolated from figure 11.

For the Galileo separation joint at a minimum load of 11.0 grains/ft,

$$\text{Explosive margin} = \frac{11.0 \text{ minimum load}}{7.0 \text{ minimum load to break}} = 1.57$$

The value of 7.0 grains/ft for minimum load to break is conservative and is based on the test series for this explosive load described in the *Results* under the *Thicknesses of Doublers and Ligaments* section. The Galileo joint doubler margin is

$$\text{Doubler margin} = \left(\frac{0.121 \text{ minimum severed thickness}}{0.065 \text{ maximum allowable thickness}}\right)^3 = 6.45$$

The 0.121-in. thickness at a minimum load of 11.0 grains/ft was obtained from table VI.

Conclusions

Following functional failures of two of five patented Lockheed Super*Zip spacecraft separation joints in a Shuttle/Centaur development test series to quantify thermal effects, an investigation program was initiated on this and related systems to assist in preventing a recurrence of failure. The Super*Zip joint is an explosively expanded (i.e., firing either of two explosive cords), preflattened tube that fractures prenotched aluminum plates in a cylindrical structure. The tube contains all explosive products. A unique test method for performance comparisons was developed to understand the severance mechanisms, the functional performance effects of system variables, and the most likely cause of system failure. An approach for defining functional margin was developed, and specific recommendations are made for improving existing and future systems. More than 300 individual test firings were conducted in meeting these goals. The test method developed for this evaluation program utilized flat, tapered-thickness aluminum plates with tapered-thickness ligaments (the material remaining beneath the notch to be severed). This approach, with properly sized plates, permitted tests to be conducted that would not allow complete severance, and thus it was possible to determine the maximum severance capability within each test firing to evaluate any particular set of test parameters. This test method was simple, relatively inexpensive (compared with complete joint testing), and proved to be highly accurate and reproducible to allow comparison of all test parameters. Finally, the tapered-plate test data were directly correlated to the performance that could be expected for actual flight hardware.

The severance mechanisms of the Super*Zip separation joint are complex. The ligament area is initially impacted by the explosive pressure wave, which induces a structural weakening. An extremely rapid bending stress-strain condition is then induced in the ligament, which ultimately fails in tension at a much smaller energy level than can be achieved with mechanical impact. The most surprising result of this investigation was that thin (0.025-in.) ligaments were more difficult to sever than thicker (0.042-in.) ligaments. This phenomenon can be attributed to the differences in the dynamic stress-strain conditions induced in the two different-thickness ligaments; in simpler terms, thin sheets can more easily be rapidly bent around small radii without fracturing than can thick sheets. Tube ruptures are induced by the explosive pressure wave driving the flattened tube radius closest to the explosive source in the dual-cord configuration into the ring structure. The tube is thinned on the peak of the radius by the initial impact and is then flattened across the entire radius against the end ring structure. As the flattened portion of the tube expands, the radius area is dynamically forced into tension, inverting the shape from convex to concave and inducing failures at the thinned sections. The single-cord configuration indicated no trend toward tube rupture with increased explosive load.

Recognizing the complexity of actual severance, we found that small variations in system parameters have a significant effect on system performance. A total of 18 identifiable variables were investigated in this study. The most influential variable was material properties (primarily hardness) of the plates (doublers); more severance (i.e., thicker doublers and ligaments severed) could be achieved with harder doubler materials. Thicknesses of doubler plates and ligaments were next in importance in influencing performance. Once the thin (0.025-in.) ligament was surpassed, the doubler (or web) thickness became more influential than the ligament thickness. The plate has to bend at the assembly bolt line before the stress-strain condition can be induced in the ligament. In fact, ligament thicknesses to 0.060 in. were demonstrated to be easier to sever than those of 0.025 in. An increase in explosive load obviously increased the thicknesses of material severed, but explosive location also increased performance. Positioning the explosive cord in line with the notches maximized the stress-strain condition to achieve severance. Changes in fastener footprint dimension affected plate bending and, consequently, severance. Halving fastener strength had no effect on performance. Reducing the free volume between the explosive cord and the tube increased output performance. However, maximizing this free volume and using flattened explosive cords with greater loads produced a higher severance capability without causing tube rupture; it also allowed a wider variation in explosive load. The criticality of this internal volume raises a challenge to the redundancy concept of two cords. If one cord is fired without achieving severance, firing the second cord will produce considerably less energy than the firing of the initial cord. Filling the free volume outside the tube with a material such as potted rubber also delivers more energy and results in more severance capability, and the tube resists rupture. To maintain tube integrity to contain explosive products, the explosive load and location must be carefully controlled. Dual-cord configurations cause considerably greater damage to the tube in firing. Flattened explosive cords greatly reduce the chance by forcing more tension into the severance thickness. More surprising results were that doubler preload, as well as vacuum and cold temperatures, had a negligible impact on functionality. Further corroborating this conclusion was no indication of change in explosive performance. The velocity of explosive propagation was consistent throughout this study under all test conditions and was approximately 23 000 ft/sec.

Based on this understanding, the most likely cause of the Shuttle/Centaur ground test failures was inadequately controlled doubler plates (i.e., too thick and too soft). A difference in plate thickness of less than 0.004 in. resulted in failure. Changing the doubler material from 7075-T6 to 7075-T73 aluminum resulted in a loss of 35.6 percent (0.050 in.) in web thickness severance capability. There is a large disparity between the functional margin of the Galileo separation joint and that of the Shuttle/Centaur joint. The Galileo explosive margin is 1.23 times greater (1.57 versus 1.27) than the Shuttle/Centaur margin, and the doubler margin is 3.77 times greater (6.45 versus 1.71) for the Galileo joint than for the Shuttle/Centaur joint.

The results of this investigation have supported program management decisions on already-incorporated system changes in enhancement of quality control and increasing the explosive load within the containment limits of the tube. The explosive load had a planned increase for Shuttle/Centaur joints from 9.0 ± 0.5 to 10.0 ± 0.5 grains/ft, for IUS joints from 9.0 ± 0.5 to a range of 9.4 to 10.0 grains/ft, and for Galileo joints from a dual-cord configuration of 9.0 ± 0.5 grains/ft to a single-cord configuration of 11.0 ± 0.5 grains/ft.

Recommendations

Recommendations for improvements in confined severance of separation joints fall into two categories: reasonable changes to existing Super*Zip systems and design goals for future confined-severance systems. Recommendations for existing Super*Zip systems are as follows:

1. Make doubler plates as thin and as hard as possible.
2. Ensure that ligament dimension selected is not so thin that severance margin is reduced.
3. Assure extrusion dimensions are maximized.
4. Demonstrate functional margins for severance for both explosive load and doubler thickness.

Recommendations for future confined-severance systems are as follows:

1. Use two complete separation joints to achieve total redundancy.
2. Use full-hardness, fracture-sensitive doubler materials.
3. Center a single explosive cord in each tube on the plates to be fractured.
4. Investigate the use of other explosive shapes, such as rectangular, which appear to direct severance energy and reduce tube rupture.
5. Minimize free volume between tube and surrounding structure.

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March 17, 1988

Reference

1. Bement, Laurence J.: Monitoring of Explosive/Pyrotechnic Performance. *Proceedings of the 7th Symposium on Explosives and Pyrotechnics*, 7E&P—71, Franklin Inst. Research Lab., Sept. 1971, pp. II-1-1–II-1-8.

Table I. Summary of Functional Tests on Five 79-in. Rings

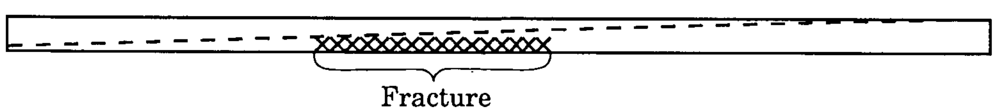
[39 doublers per ring]

Doubler thickness, in.	Number of doublers	Number of failures[a]	Percentage of failures
0.079 to 0.083	124	0	0
.085	1	0	0
.086	24	2	8.3
.087	35	7	20.0
.088	11	4	36.4

[a]All failures occurred in two tests at approximately −80°F and −120°F.

Table II. Investigation of Ligament Thickness

[Test parameters—8.5 grains/ft HMX; single-cord configuration; constant-thickness plate; 0.035-in. tube wall; large extrusion (0.200 in.); tapered ligament (0.015 in. to runout)]



Cross section of plate for test 17

Test	Plate	Rockwell B hardness	Plate thickness, in.	Thickness fractured, in.
15	LXI	78	0.106	0
	LXII	78	.106	0
16	LXV	78	.086	.016 to .022
	LXVI	78	.086	.016 to .020
				.028 to .070
17	LXVIII	78	.081	.038 to .053
	LXVII	78	.081	.025 to .069

Table III. Tapered-Plate Performance Standard

[Test parameters—8.95 grains/ft HMX; dual-cord configuration; standard tube and extrusion (12 in.); 0.123- to 0.065-in. tapered plate; 0.095- to 0.037-in. tapered alignment; 0.312-in.-diameter fastener footprint]

Test	Plate	Rockwell B hardness	Thickness fractured, in.	
			Web	Ligament
158	CCL	77	0.089	0.063
	CCLI	79	.089	.065
159	CCLII	76	.085	.059
	CCLIII	79	.091	.065
160	CCLIV	78	.090	.063
	CCLV	79	.086	.056
161	CCLVI	78	.090	.063
	CCLVII	79	.093	.065
162	CCLVIII	77	.090	.064
	CCLVIX	79	.096	.067
Average			0.0899	0.063
Standard deviation			0.0031	0.0032

Table IV. Accelerated Aging of 7075-T6 Aluminum

Thermal exposure[a]	Rockwell B hardness		Conductivity, percent	
	Target	Actual	Target	Actual
As received		89–90		33
315°F/24 hr	78 (77 min.)	85	41 (38 min.)	[b]35
335°F/30 hr	78 (77 min.)	[b]69	41 (38 min.)	42
325°F/24 hr	78 (77 min.)	79–80	41 (38 min.)	41.5
325°F/27 hr	78 (77 min.)	79	41 (38 min.)	41.5

[a]To obtain 7075-T73, expose 7075-T6 to heats of 315°F to 335°F for 24 to 30 hours (MIL-H-6088F).

[b]Cause for rejection.

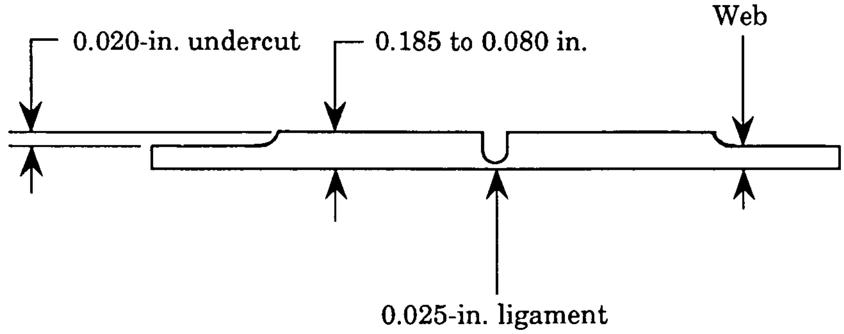
Table V. Functional Performance of 7075-T6 Aluminum

[Test parameters—9.0 grains/ft HMX; dual-cord configuration; standard tube and extrusion (12 in.); 0.183- to 0.062-in. tapered plate (11 in.); full shank bolts; 0.312-in.-diameter washers]

Test	Plate	Rockwell B hardness	Thickness fractured, in.	
			Web	Ligament
216	1	90	0.140	0.112
	2	90	.134	.109
217	3	90	.150	.122
	4	90	.135	.107
218	5	90.5	.142	.115
	6	90.5	.140	.112
219	7	90.5	.141	.111
	8	90.5	.136	.108
220	9	91	.142	.113
	10	91	.136	.108
Average			0.1396	0.1117
Standard deviation			0.0047	0.0044

Table VI. Functional Performance of Galileo Tapered-Plate Joint

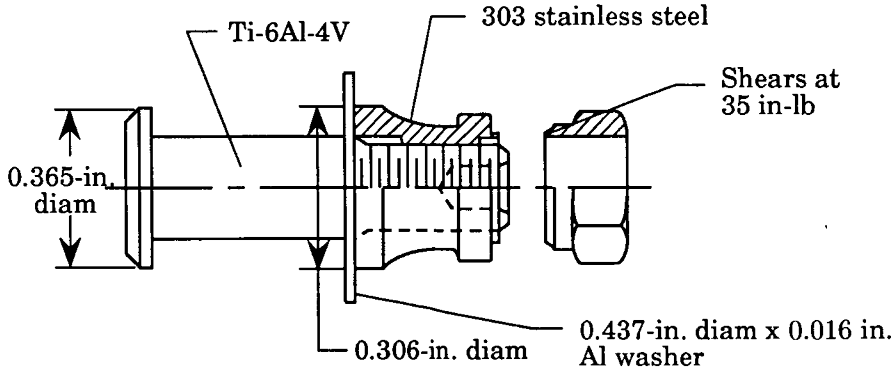
[Test parameters—11.2 grains/ft HMX; single-cord configuration; 0.185- to 0.080-in. tapered plate (11 in.); 0.025 ± 0.002-in. constant-thickness ligament; 0.200-in. extrusion; full shank bolt]



Test	Plate	Rockwell B hardness	Thickness fractured, in.	
			Web	Ligament
225	1	81	0.125	0.024
	2	81	.118	.025
226	3	81	.120	.025
	4	81	.126	.024
227	5	80	.121	.024
	6	81	.122	.025
228	8	80	.118	.024
	9	80	.116	.024
229	11	80	.126	.027
	12	80	.118	.025
Average			0.121	
Standard deviation			0.0037	

Table VII. Functional Performance of Hi-Lok Fastener

[Test parameters—8.65 grains/ft HMX; dual-cord configuration; standard tube and extrusion (12 in.); 0.123-in. tapered plate; data show fracture in plate beneath bolt head and nut]

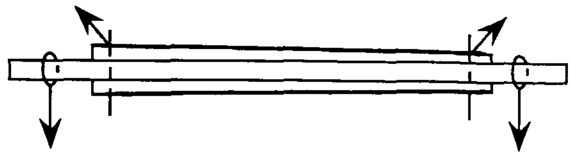


Test	Component	Plate	Rockwell B hardness	Thickness fractured, in. Web	Thickness fractured, in. Ligament
136	Bolt	CCXXI	76.0	0.089	0.064
	Nut	CCXXII	75.0	.093	.067
[a]137	Bolt	CCXXIV	75.0	.087	.062
	Nut	CCXXIII	77.3	.094	.067
138	Bolt	CCXXV	77.5	.083	.059
	Nut	CCXXVI	76.3	.090	.063
139	Bolt	CCXXVII	76.3	.085	.060
	Nut	CCXXVIII	76.5	.092	.065
Average: Bolt				0.086	0.0613
Nut				.0923	.0655
Standard deviation: Bolt				0.0026	0.0023
Nut				.0017	.0019

[a]No washer.

Table VIII. Functional Effect of Doubler Preloads

[Test parameters—8.5 grains/ft HMX; single-cord configuration; 0.123- to 0.066-in. tapered plate (8 in.); 0.035-in. tube wall; large extrusion (0.200 in.)]



Test	Weight, lb	Plate	Rockwell B hardness	Tube position	Thickness fractured, in.	
					Web	Ligament
45	20	CXXIII	75.3	Top	0.103	0.074
		CXXIV	75.0	Bottom	.100	.071
46	50	CXXVI	75.5	Top	.097	.066
		CXXV	74.8	Bottom	.102	.072
47	100	CXXVIII	75.5	Top	.096	.066
		CXXVII	75.0	Bottom	.096	.066

Table IX. Functional Effect of Cold Temperatures

[Test parameters—9.0 grains/ft HMX; dual-cord configuration; standard tube and extrusion (12 in.); 0.123-in. tapered plate (8 in.); full shank bolts; 0.312-in.-diameter washers; stabilized at temperature for 15 minutes]

Test	Temperature, °F	Plate	Rockwell B hardness	Thickness fractured, in.	
				Web	Ligament
207	−20	CCLXXVI	79	0.088	0.059
		CCLXXXVII	79	.086	.058
208	−40	CCLXXXVIII	79	.090	.060
		CCLXXXIX	79.5	.092	.064
209	−60	CCXC	80	.096	.066
		CCXCI	79	.093	.065
210	−80	CCXCII	79	.088	.059
		CCXCIII	78	.086	.057
211	−120	CCXCIV	79	.087	.061
		CCXCV	78	.090	.062
212	−160	CCXCVI	78	.087	.057
		CCXCVII	79	.088	.057
213	−200	CCXCVIII	78	.095	.066
		CCXCVIX	78	.090	.062
Average				0.0897	0.0609
Standard deviation				0.0032	0.0033

Table X. Flare Measurement Comparisons at Cold Temperatures

[Test parameters—dual-cord configuration; standard tube and extrusion; high-fidelity fixture; 0.082-in. web and 0.042-in. ligaments]

Test	Temperature, °F	Explosive load, grains/ft	Top flare, in.		Bottom flare, in.	
			Average	Standard deviation	Average	Standard deviation
176	Lab ambient	9.0	0.721	0.0084	0.801	0.0069
177 to 181	Lab ambient	7.5	.670	.005	.702	.012
182	−30	7.6	.650	.0101	.668	.0110
183	−35	7.6	.643	.0102	.660	.112
185	−65	9.0	.686	.0069	.7375	.0083

Table XI. Results for High-Fidelity Tapered-Plate Validation Tests

[Test parameters—dual-cord configuration; standard tube and extrusion; high-fidelity fixture; 0.042-in. ligaments]

Test	Explosive load, grains/ft	Plate thickness, in.	Top flare, in.		Bottom flare, in.	
			Average	Standard deviation	Average	Standard deviation
177 to 181	7.5	0.082	0.670	0.005	0.702	0.012
252	11.1	.122	.782	.008	.772	.009
253	10.9	.122	[a].788	.007	.777	.009
256	8.9	.095	.747	.006	.782	.009
257	9.1	.095	.724	.007	.746	.011

[a]Doublers gripped tube; 20 lbf required to disengage.

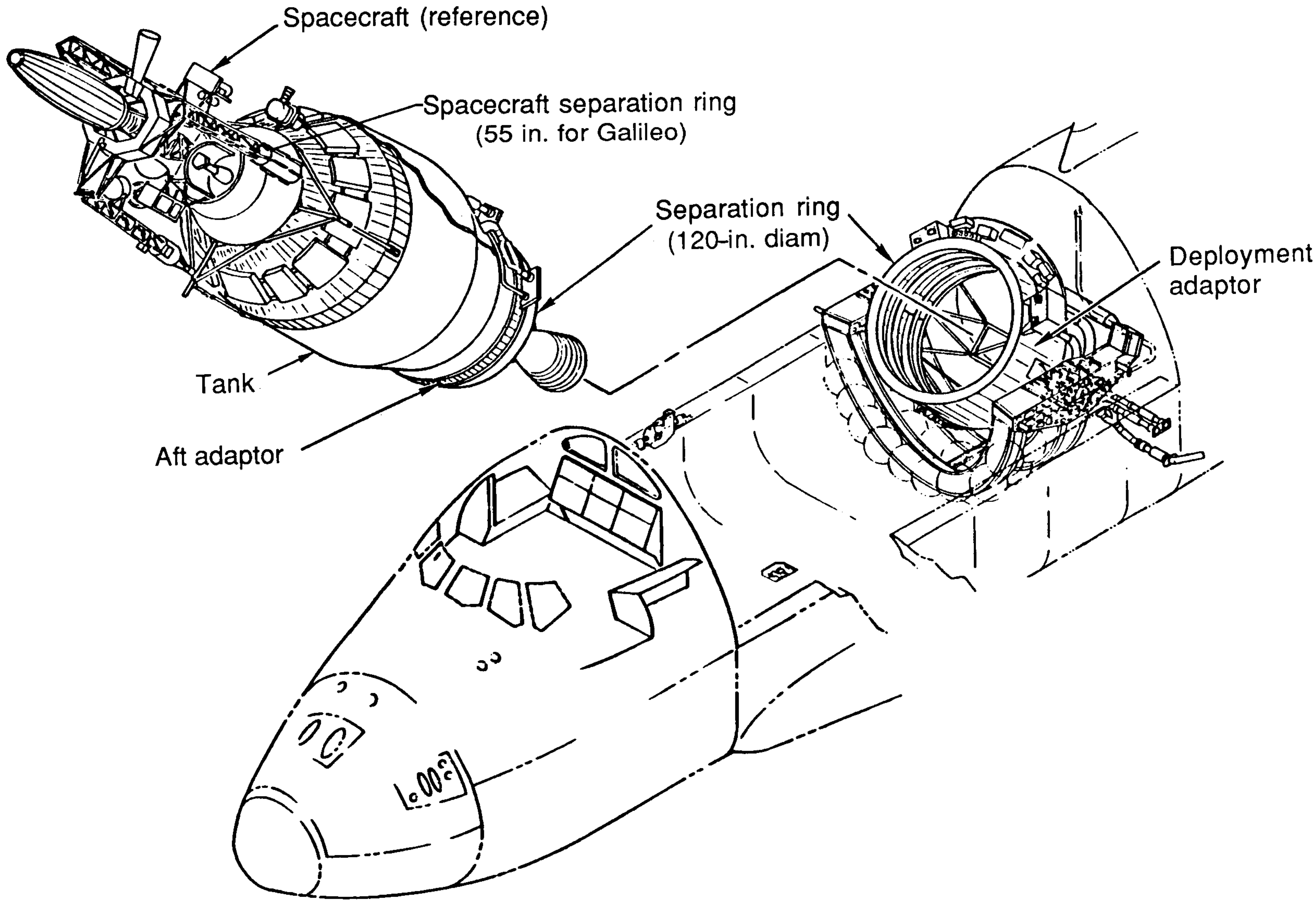


Figure 1. Shuttle/Centaur deployment system.

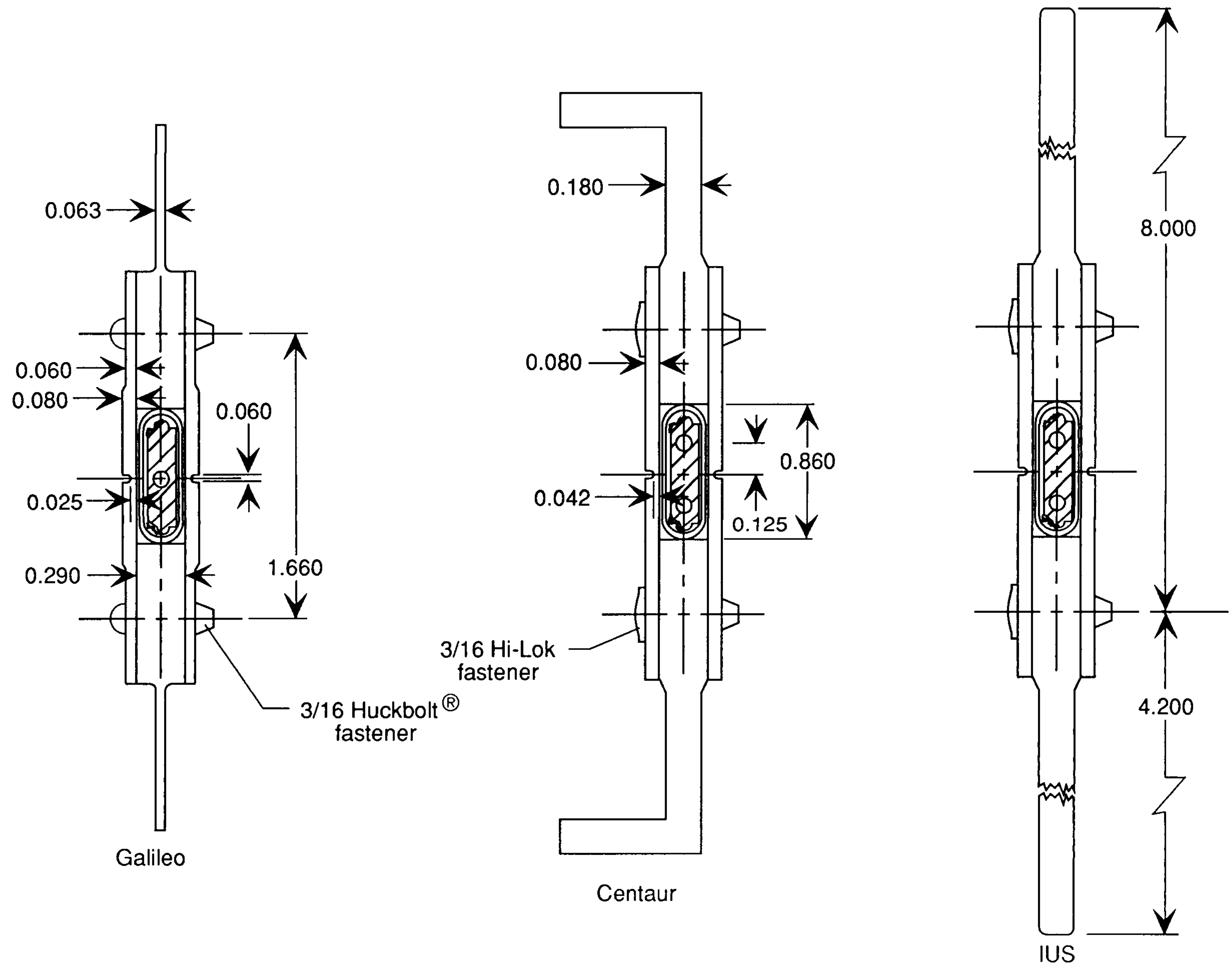


Figure 2. Cross sections of Galileo, Centaur, and IUS separation joints. ®Huckbolt: registered trademark of Huck Manufacturing Co.

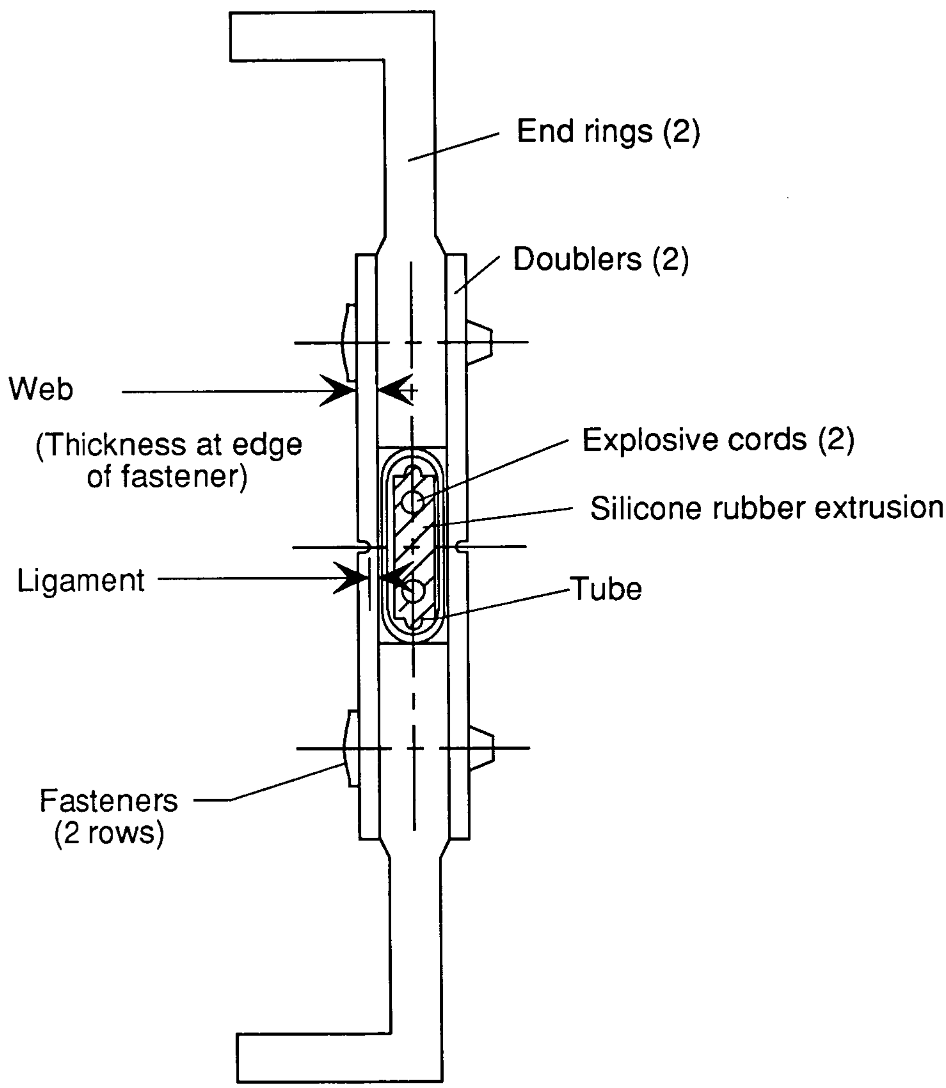


Figure 3. Component identification of separation joint.

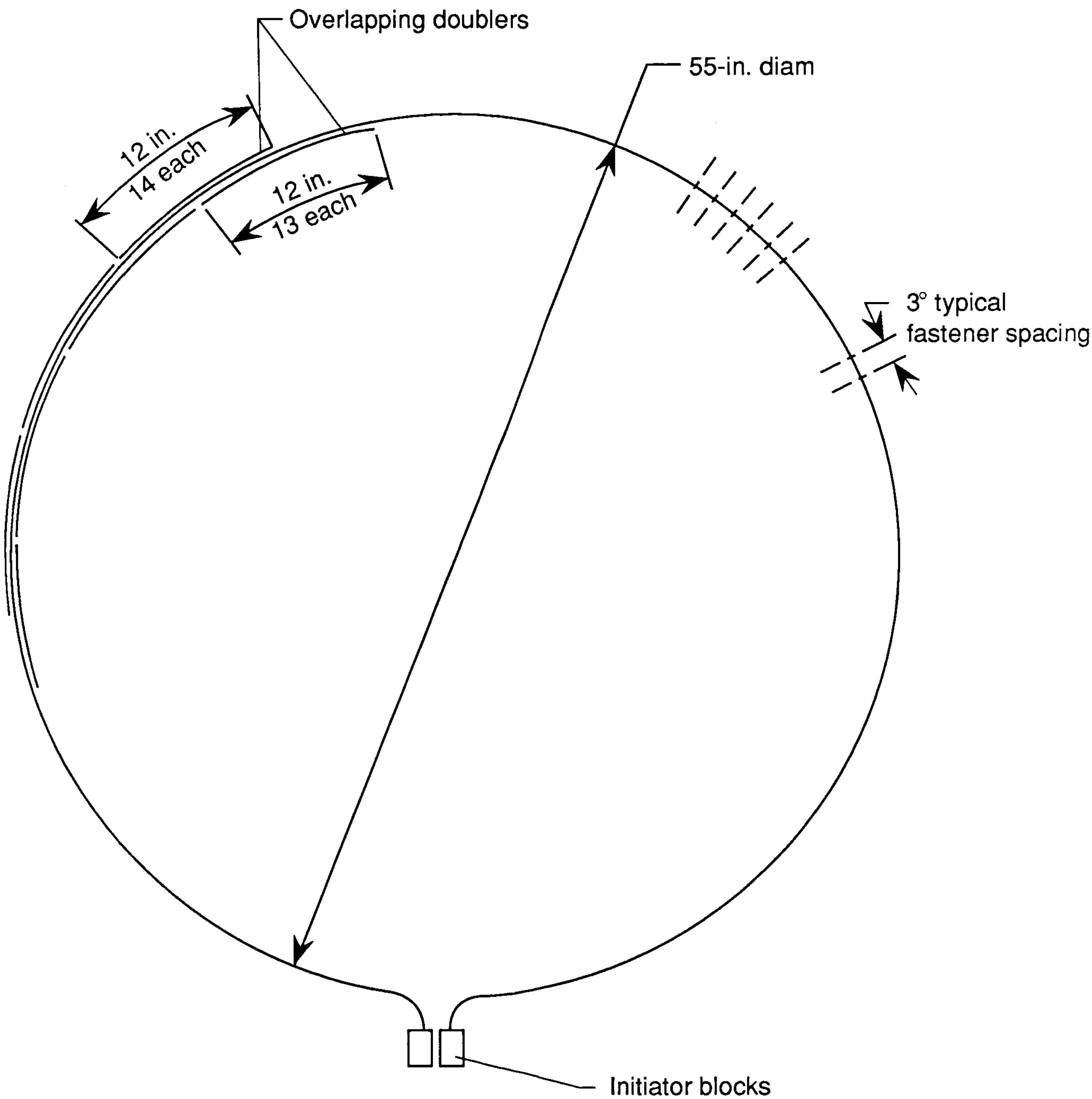
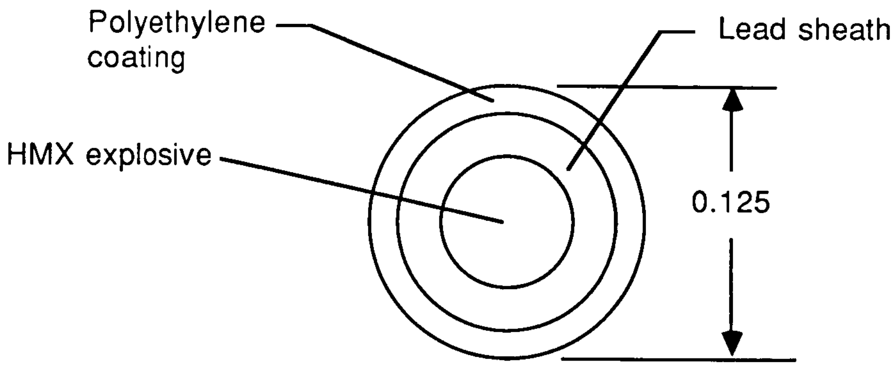
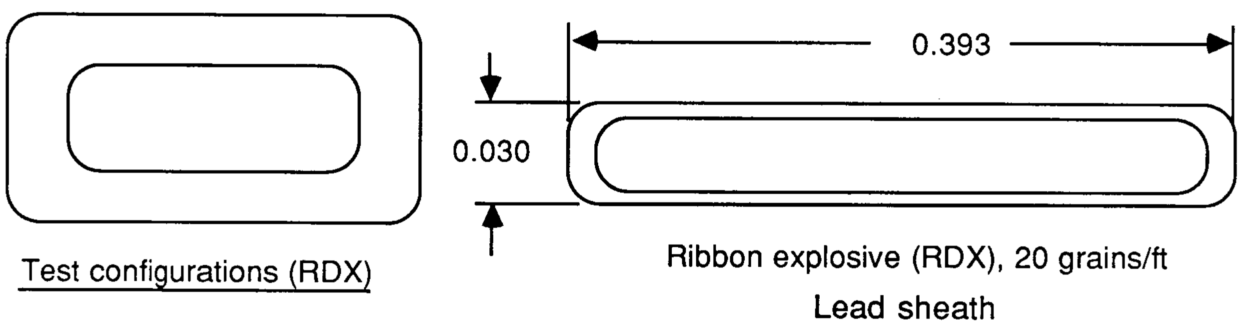


Figure 4. Top view of Galileo separation joint.





Explosive load, grains/ft	Sheath	Dimensions
20	Al	0.197 x 0.062
15	Pb	0.160 x 0.055
7.5	Al	0.115 x 0.040
5	Pb	0.088 x 0.027

Figure 5. Cross-sectional dimensions of explosive cords used. Linear dimensions are in inches.

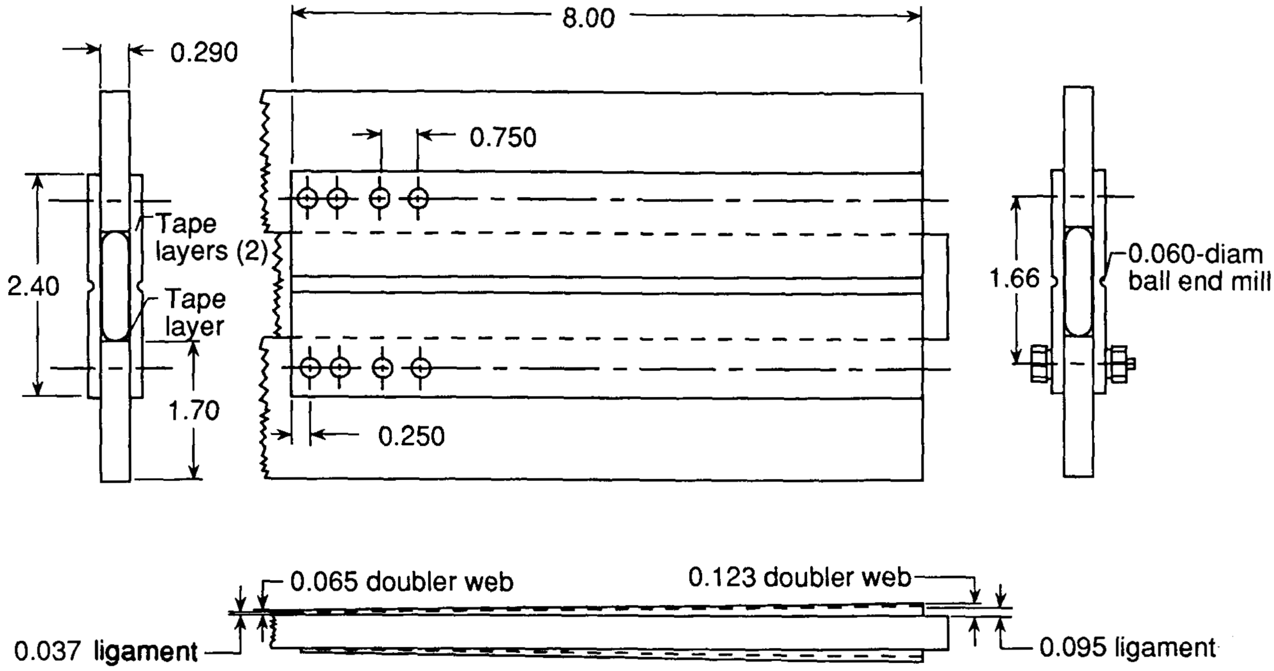


Figure 6. Separation-joint tapered-plate test configuration (lightweight plates). Heavyweight plates were 11 in. long and tapered from 0.183 to 0.065 in. All linear dimensions are in inches.

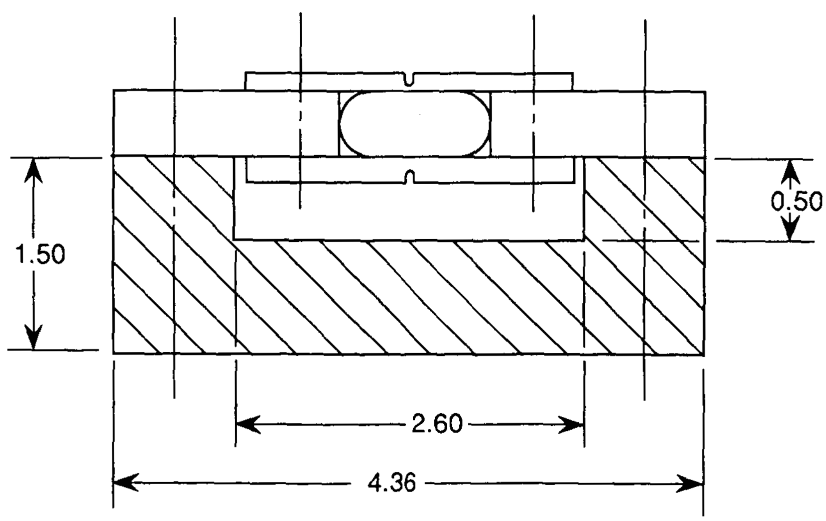
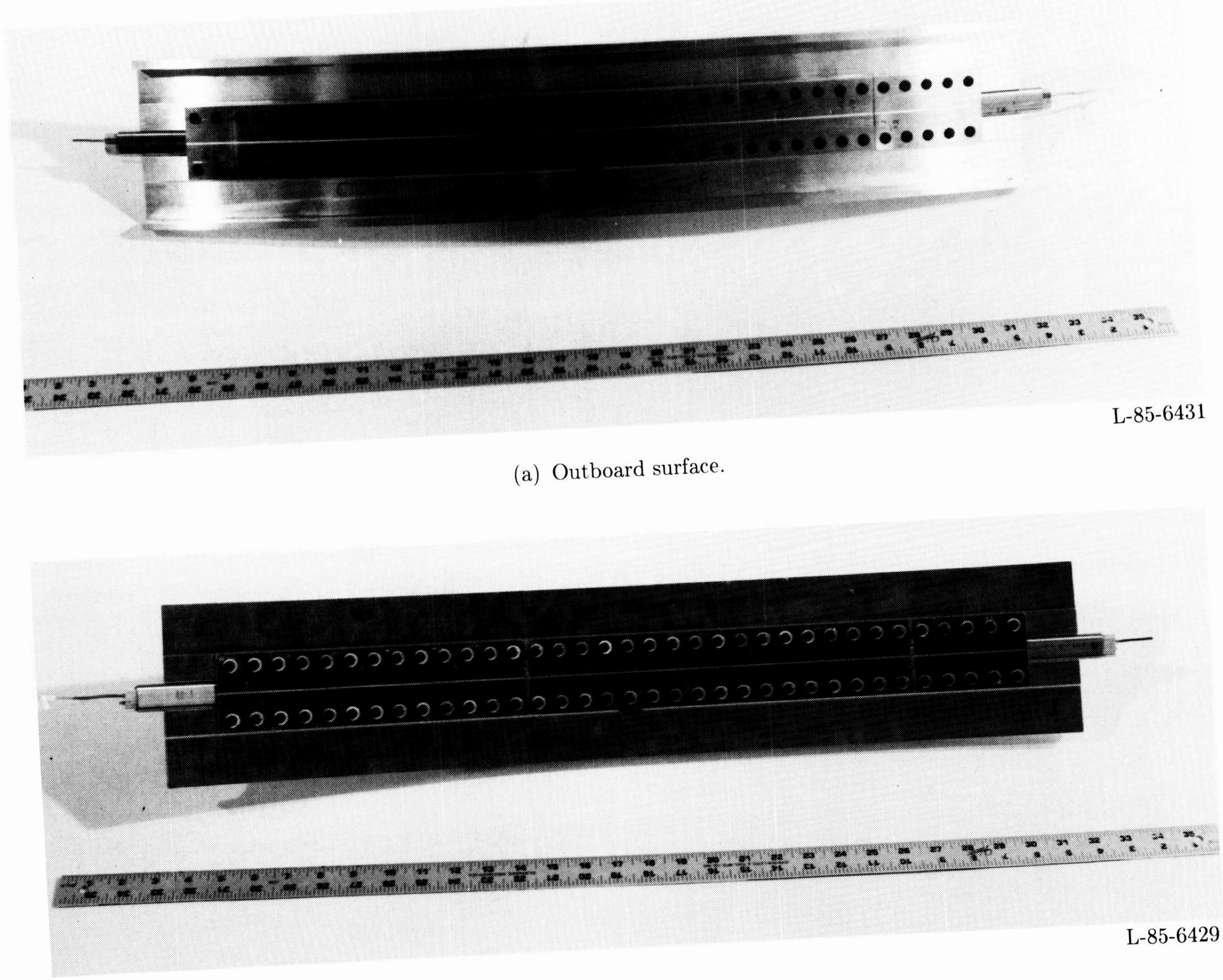


Figure 7. Rigid test fixture. Linear dimensions are in inches.



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(a) Outboard surface.

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(b) Inboard surface.

Figure 8. High-fidelity test panel.

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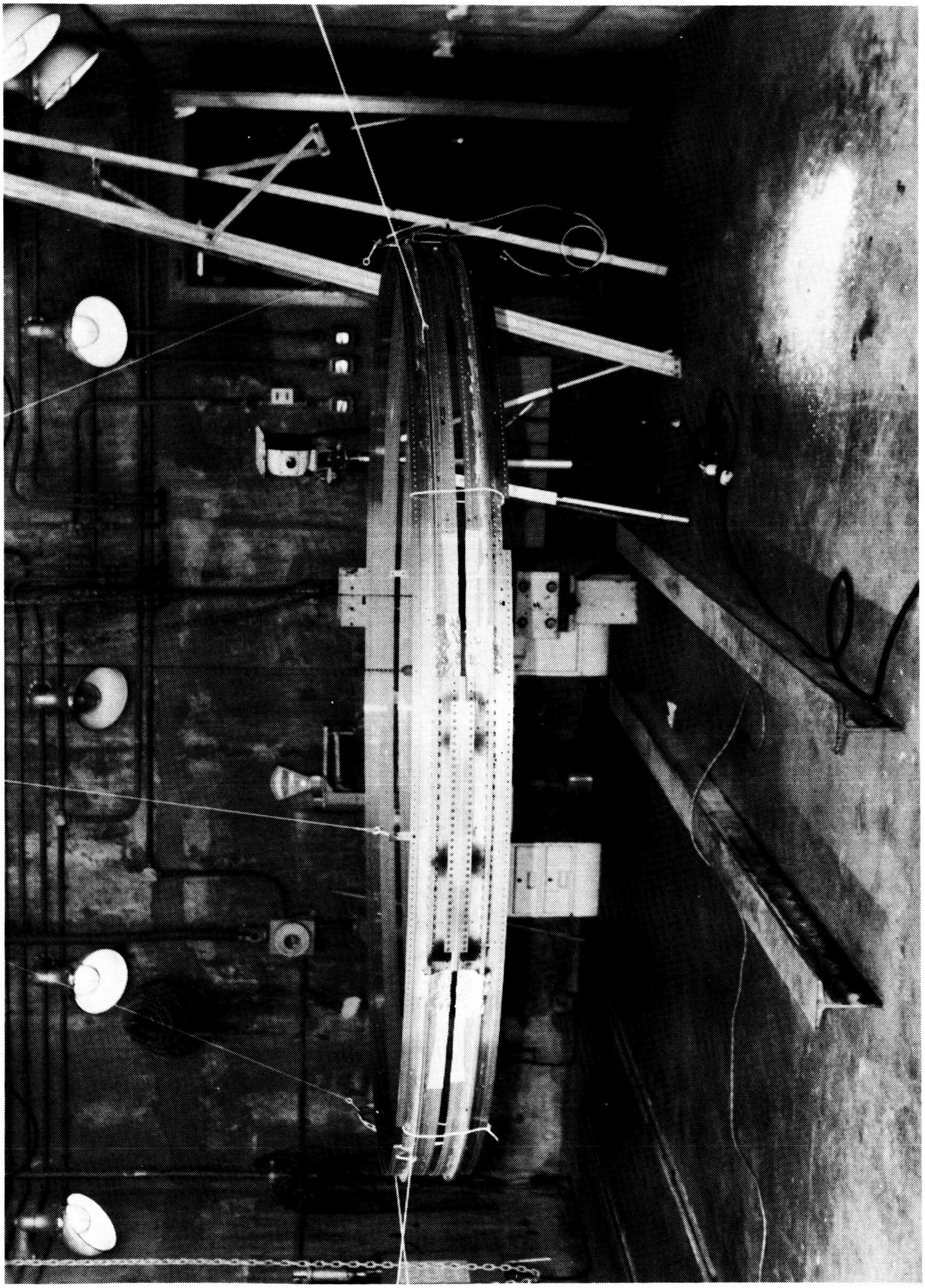

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Figure 9. View of test setup for high-fidelity panel on 120-in.-diameter Shuttle/Centaur separation-joint rings.

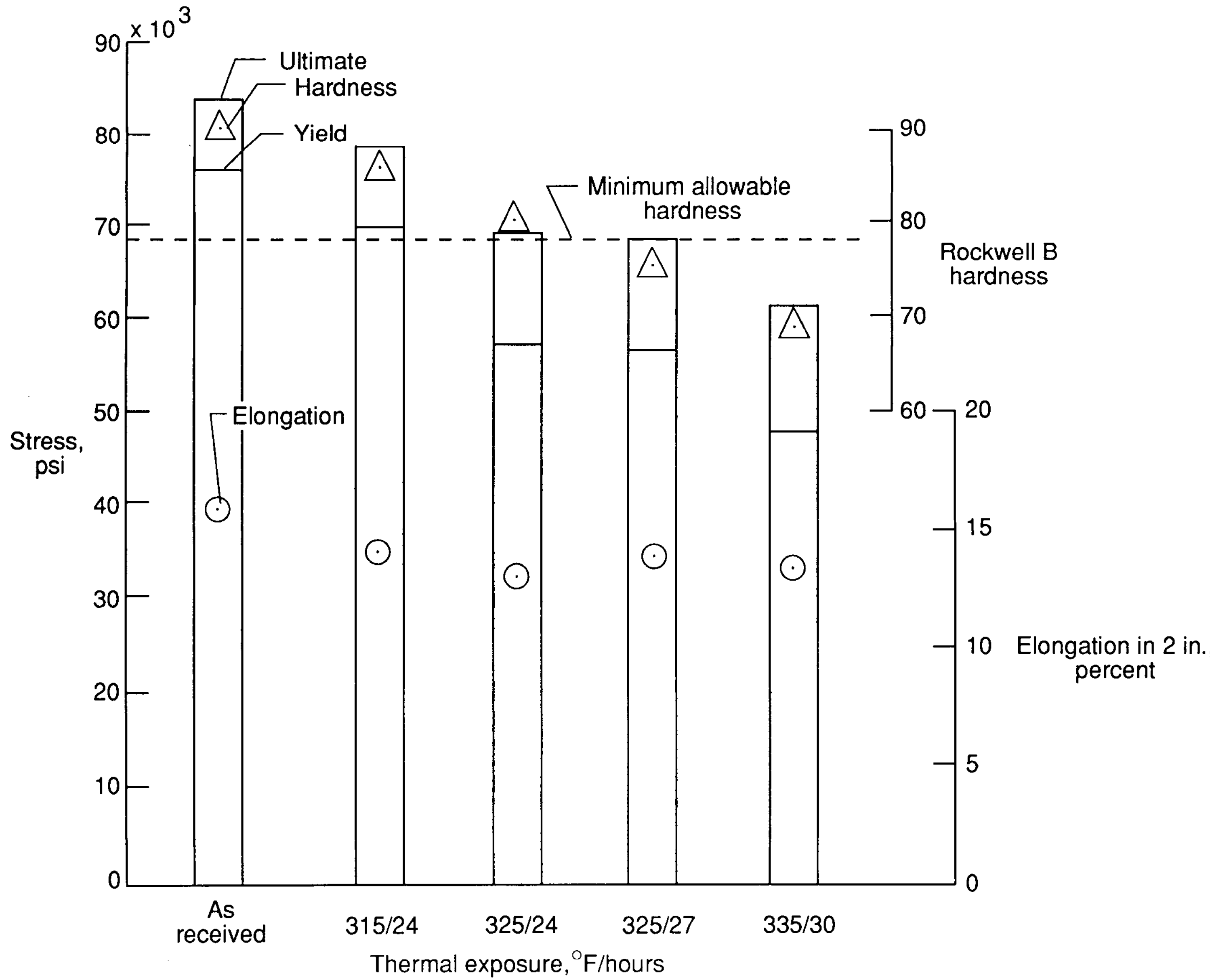

Figure 10. Mechanical properties of heat-treated 7075-T6 aluminum.

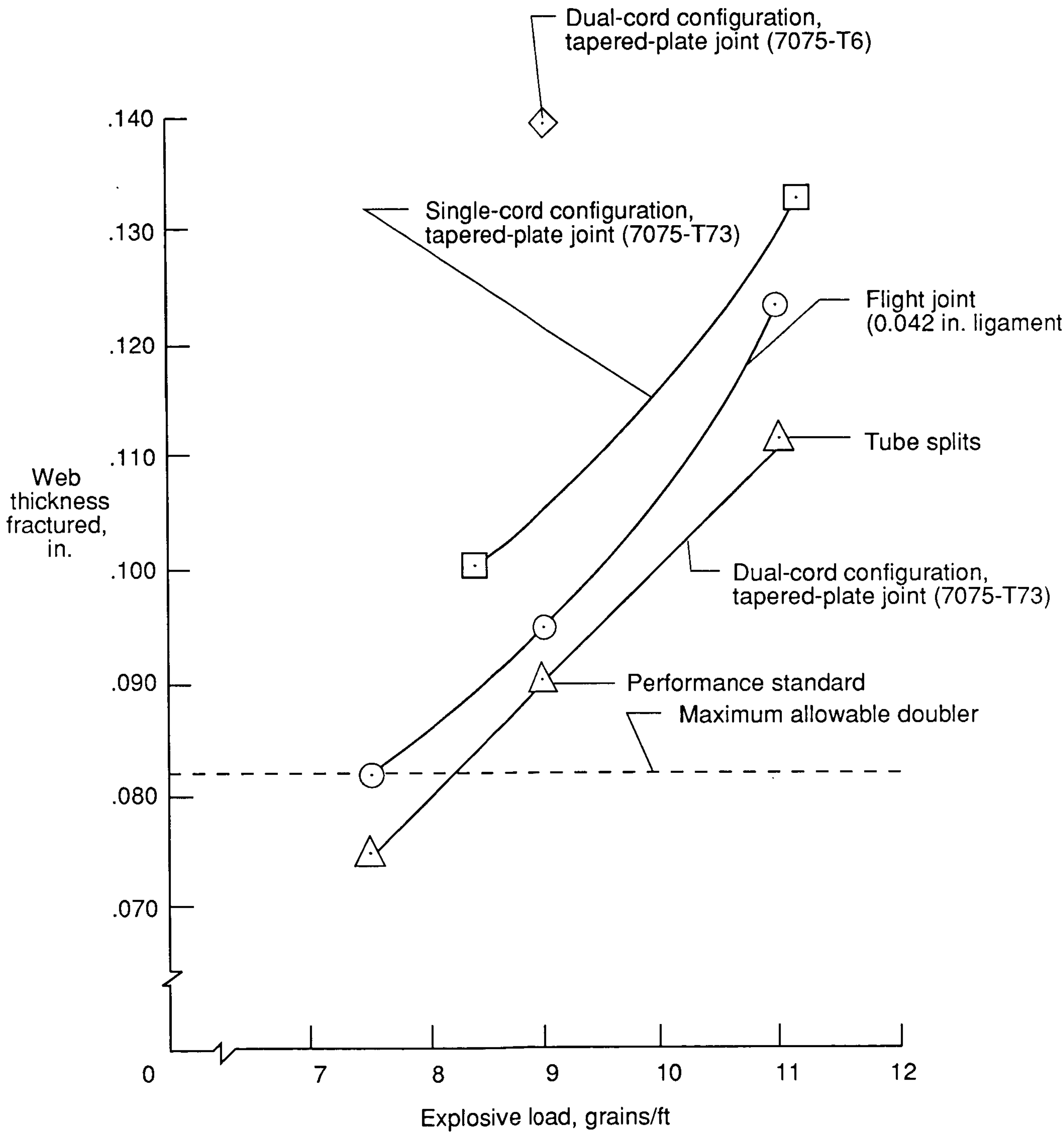

Figure 11. Severance performance of different test configurations.

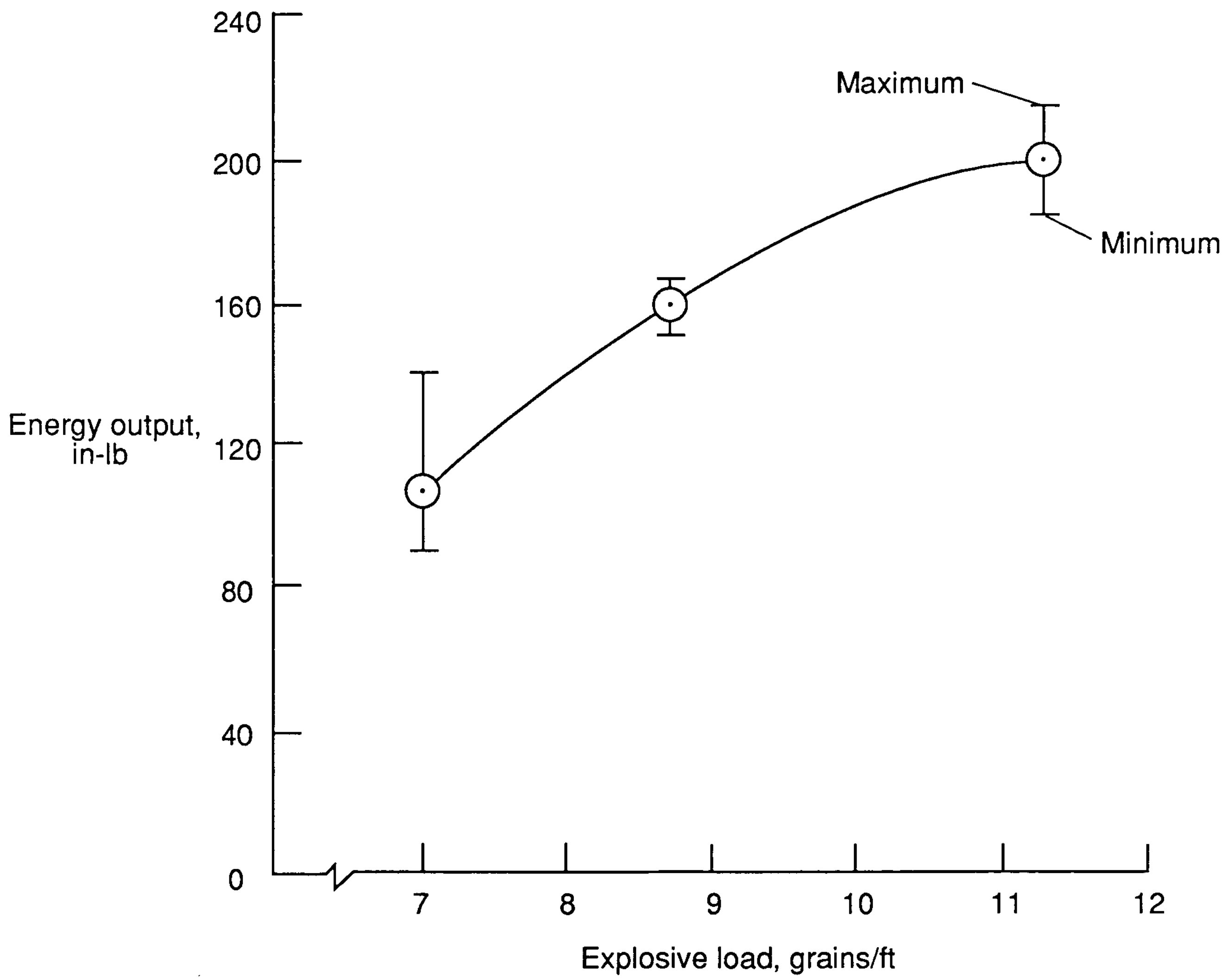

Figure 12. Energy output produced by expanding tube with different explosive loads for dual-cord configuration.

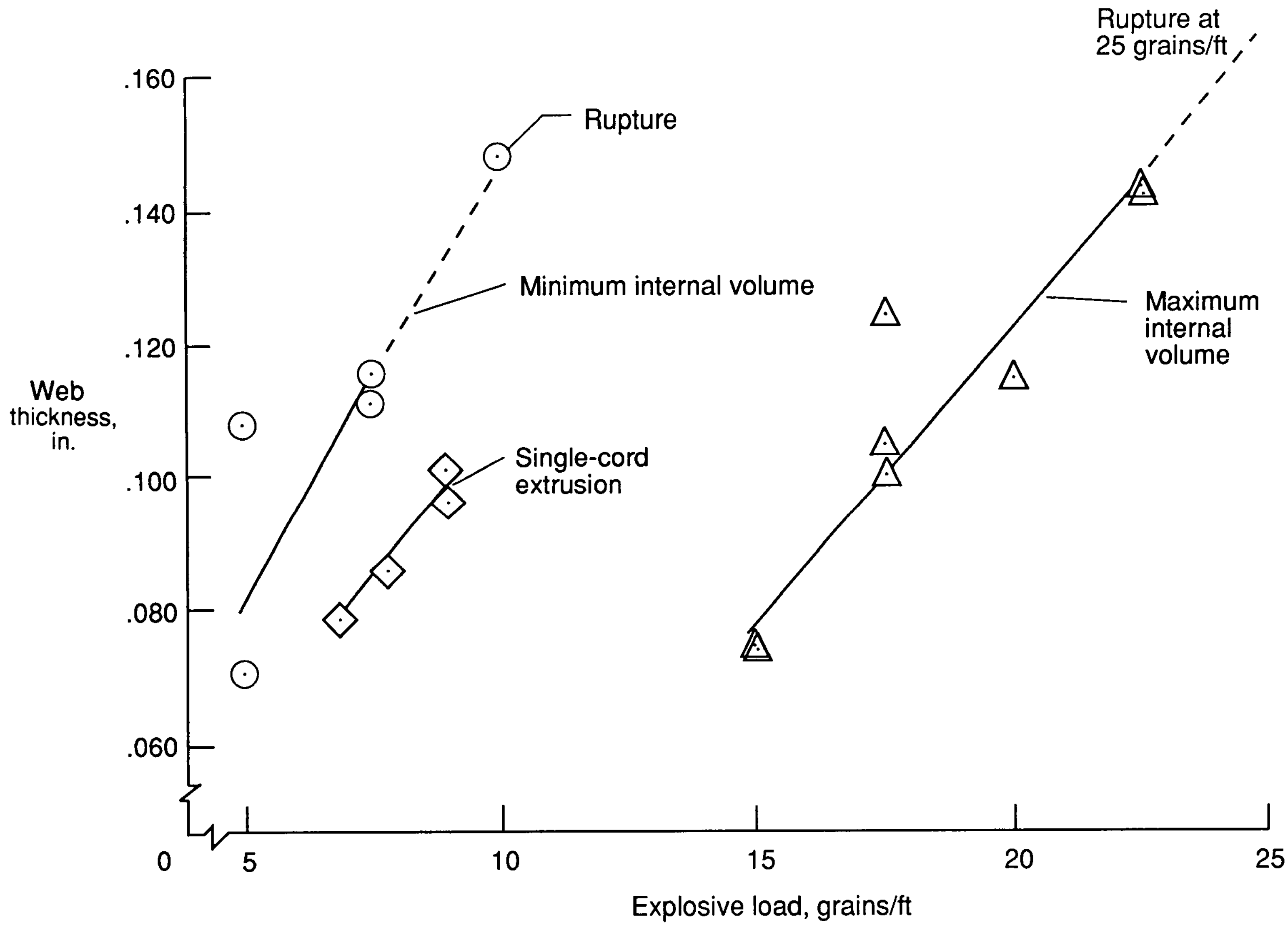

Figure 13. Performance evaluation of changes to internal volume within tube.

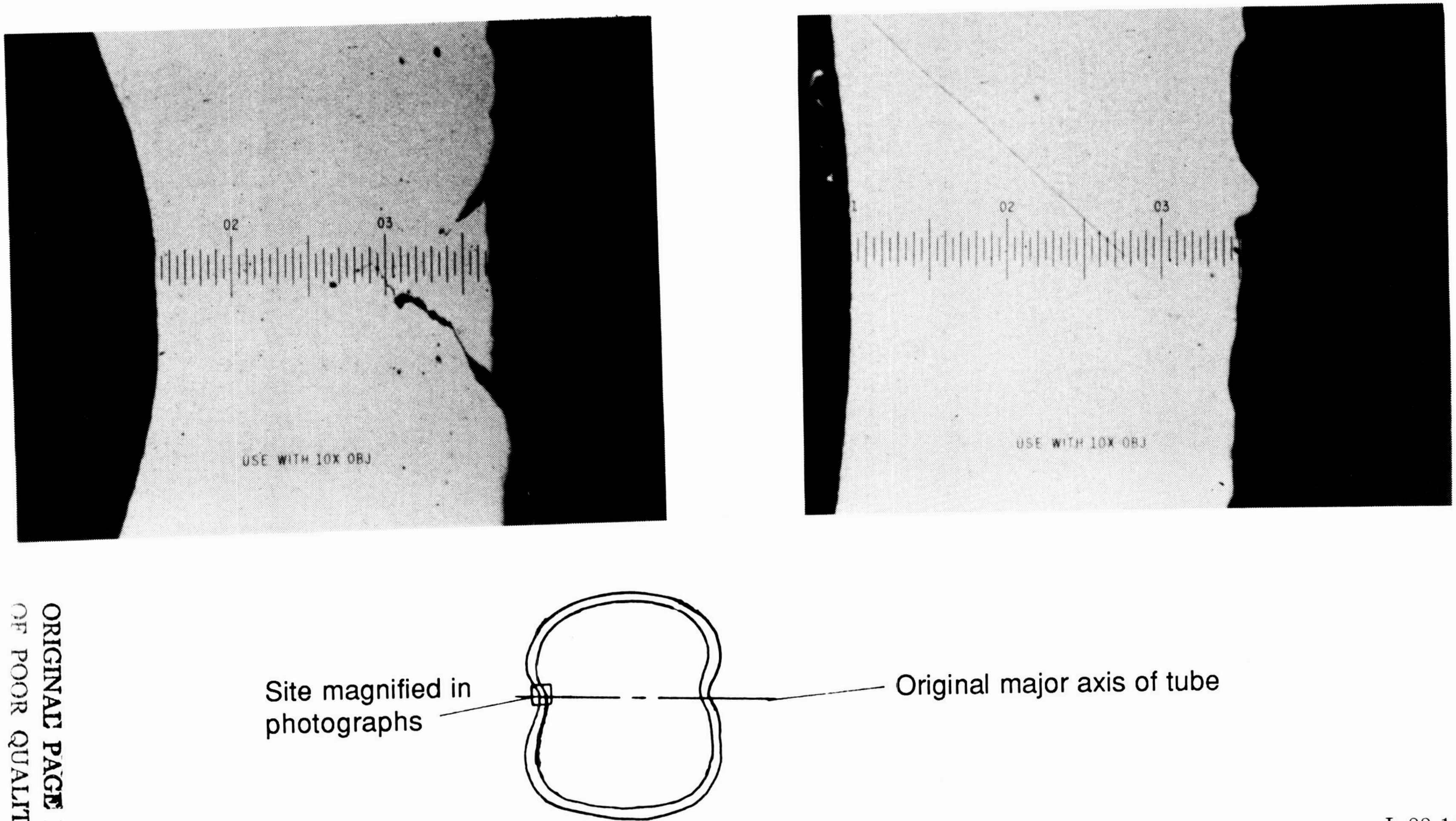

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Figure 14. Cross sections of post-test tubes at site of tube ruptures. The scale is in hundredths of an inch.

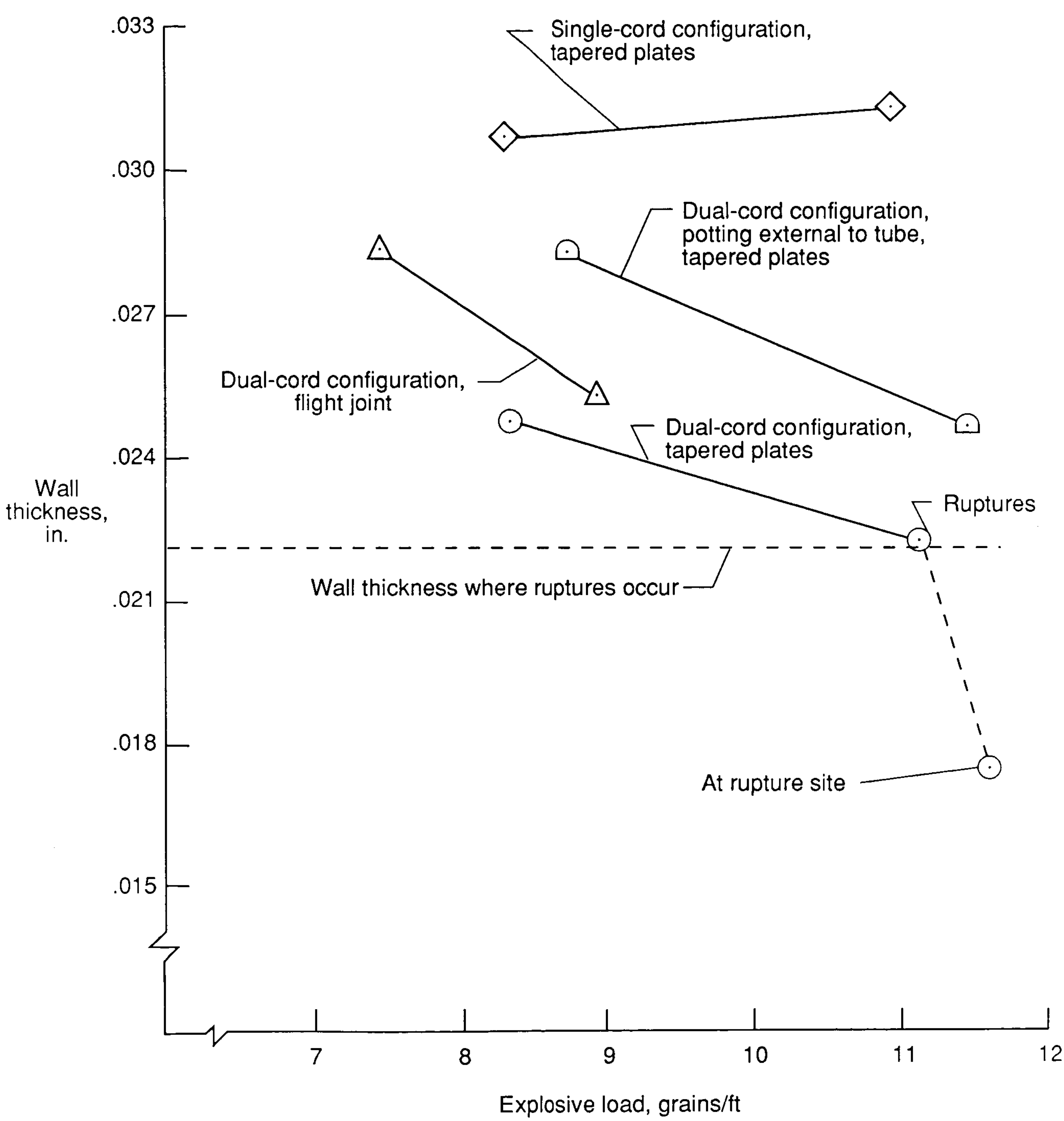

Figure 15. Typical post-test tube wall thicknesses for various configurations. Original wall thickness was 0.035 in.

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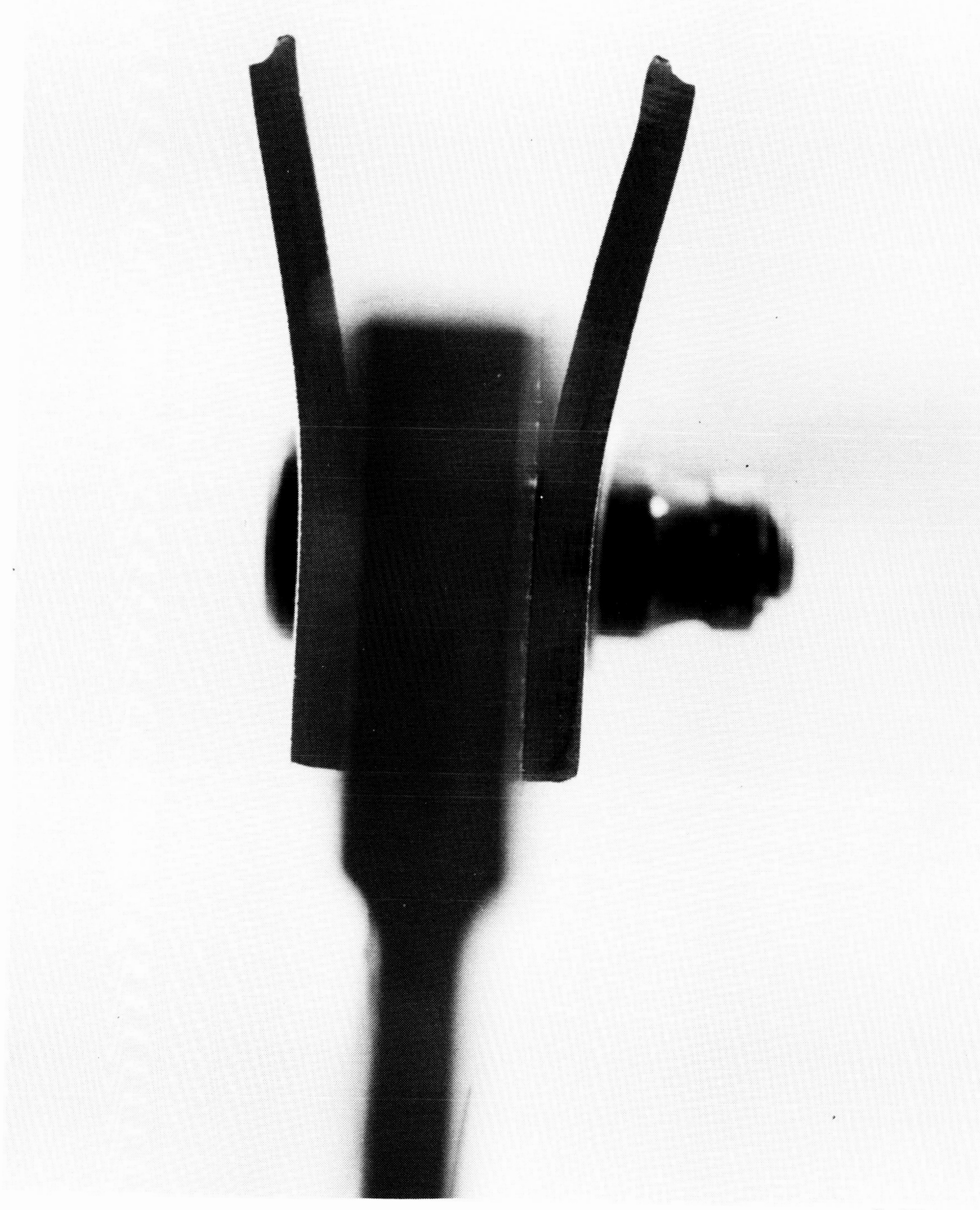

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Figure 16. End view of flared, fractured doublers.

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16. Abstract

This report describes an investigation to determine the most likely cause of two failures of five tests on 79-in.-diameter Lockheed "Super*Zip" spacecraft separation joints being used for the development of a Shuttle/Centaur propulsion system. This joint utilizes an explosively expanded tube to fracture surrounding prenotched aluminum plates to achieve planar separation. A unique test method was developed and more than 300 test firings were made to provide an understanding of severance mechanisms and the functional performance effects of system variables. An approach for defining functional margin was developed, and specific recommendations were made for improving existing and future systems.

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