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AFML-TR-74-107

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EXPLORATORY DEVELOPMENT OF NEW AND IMPROVED SELF-SEALING MATERIALS FOR FUEL LINES

NORTHROP CORPORATION
AIRCRAFT DIVISION
HAWTHORNE, CALIFORNIA 90250

OCTOBER 1974

FINAL REPORT COVERING PERIOD 26 FEBRUARY 1973 – 15 MARCH 1974

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This final report was submitted by the Northrop Corporation, Aircraft Division, Hawthorne, California, under USAF Contract F33615-73-C-5056, Job Order No. 73400552, with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. T. L. Graham (MBE) was the laboratory project monitor.

This technical report has been reviewed and is approved for publication.

T L Graham

T. L. GRAHAM
Project Monitor

FOR THE COMMANDER

MERRILL L. MINGES, Chief
Elastomers and Coatings Branch
Nonmetallic Materials Division

AIR FORCE/56780/16 December 1974 — 100

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
AFML-TR-74-107

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
EXPLORATORY DEVELOPMENT OF NEW AND IMPROVED SELF-SEALING MATERIALS FOR FUEL LINES

5. TYPE OF REPORT & PERIOD COVERED
Final Report
26 Feb 73 - 15 Mar 74

6. PERFORMING ORG. REPORT NUMBER
NOR 74-63

7. AUTHOR(s)
R. M. Heitz
F. Hill

8. CONTRACT OR GRANT NUMBER(s)
F33615-73-C-5056

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Northrop Corporation, Aircraft Division
3901 West Broadway
Hawthorne, California 90250

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Project No. 7340
Task No. 734005

11. CONTROLLING OFFICE NAME AND ADDRESS
Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson AFB, Ohio 45433

12. REPORT DATE
June 1974

13. NUMBER OF PAGES
67

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
NA

16. DISTRIBUTION STATEMENT (of this Report)
Distribution limited to U.S. Government agencies only (test and evaluation); October 1974. Other requests for this document must be referred to the Air Force Materials Laboratory, Nonmetallic Materials Division, Elastomers and Coatings Branch, AFML/MBE, Wright-Patterson Air Force Base, Ohio 45433.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Damage Control Systems
Self-Sealing Systems
Projectile (AP)
Fuel Lines
Shock Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

New and improved self-sealing fuel line composites were developed under this program. Fabric reinforced plastic and nonflowering integrated aluminum foil, fabric reinforced laminated fuel line composites employing compressed natural rubber foam as the sealant were fabricated which successfully sealed wounds inflicted by .30 and .50 caliber projectiles. The weight of these new self-sealing fuel line composites ranged from 0.83 to 1.28 lbs/ft^2. A standard aluminum fuel line provided with a conventional self-sealing protective cover capable of sealing wounds inflicted by .50 caliber projectiles

20. ABSTRACT (Continued)

nominally weighs 2.59 lbs/ft^2. Results of pressure tests demonstrated the fabric reinforced plastic fuel line and certain fuel line composite based on plies of aluminum foil reinforced with plies of ballistic nylon fabric to be capable of withstanding hydraulic pressure in excess of 240 psi and resistant to distortion under (29.5 inches of Hg) vacuum. The compressed foam self-sealing concept utilizing plies of ballistic nylon for controlling damage was also investigated as a means of protecting standard aluminum fuel line tubing. The self-sealing compressed foam composite evaluated for protecting a standard aluminum fuel line was found to be effective for sealing wounds inflicted by .30 caliber projectiles but proved to be inadequate at the .50 caliber projectile threat level.

FOREWORD

This report was prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California, under USAF Contract F33615-73-C-5056. The contract work was performed under Project No. 7340, "Nonmetallic and Composite Materials," Task No. 734005, "Elastomeric and Compliant Materials." It was administered under the direction of the Nonmetallic Materials Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. T. L. Graham (MBE) as the Project Monitor.

Dr. R. M. Heitz served as the Principal Investigator on this program. Other Northrop personnel who made major contributions in this research program were Dr. G. H. Bischoff, F. Hill, V. L. Johnson, and H. Miller.

The contractor's report number is NOR 74-63. This report covers work from 26 February 1973 through 15 March 1974.

This report was submitted by authors 25 March 1974.

ABSTRACT

New and improved self-sealing fuel line composites were developed under this program. Fabric reinforced plastic and nonflowering integrated aluminum foil, fabric reinforced laminated fuel line composites employing compressed natural rubber foam as the sealant were fabricated which successfully sealed wounds inflicted by .30 and .50 caliber projectiles. The weight of these new self-sealing fuel line composites ranged from 0.83 to 1.28 lbs./ft^2. A standard aluminum fuel line provided with a conventional self-sealing protective cover capable of sealing wounds inflicted by .50 caliber projectiles nominally weighs 2.59 lbs./ft^2. Results of pressure tests demonstrated the fabric reinforced plastic fuel line and certain fuel line composite based on plies of aluminum foil reinforced with plies of ballistic nylon fabric to be capable of withstanding hydraulic pressure in excess of 240 psi and resistant to distortion under (29.5 inches of Hg) vacuum. The compressed foam self-sealing concept utilizing plies of ballistic nylon for controlling damage was also investigated as a means of protecting standard aluminum fuel line tubing. The self-sealing compressed foam composite evaluated for protecting a standard aluminum fuel line was found to be effective for sealing wounds inflicted by .30 caliber projectiles but proved to be inadequate at the .50 caliber projectile threat level.

TABLE OF CONTENTS

CONTENTS (Continued)

Section Page

LIST OF ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION I

INTRODUCTION

Limited war operations have demonstrated that a considerable hazard still exists from small arms and anti-aircraft ground fire. Penetration of an aircraft fuel system by a 20mm or smaller projectile can produce fuel leaks leading to fuel starvation, fires, explosions, or catastrophic destruction of an aircraft. In the past, the bulk of the effort in the area of self-sealing fuel lines has been devoted to the development of self-sealing protective covers (e.g., self-sealing fuel cell materials) for metallic fuel lines which tend to flower or petal when punctured by a projectile. Although some success has been realized at the .50 caliber level threat, the conventional protective cover approach has not proved entirely satisfactory. Because of this flowering tendency metallic fuel lines, more sealant must be applied than would be required if petalling did not occur; consequently, excessive weight and volume penalties have resulted. The development of self-sealing fuel lines which do not flower when punctured appears to be a method of improving sealing efficiency and minimizing weight and volume penalties.

The objective of this investigation was the development of a non-flowering self-sealing fuel line material for protecting fuel lines against .50 and .60 caliber AP projectiles penetrating at normal incidence, and .30 caliber AP projectiles penetrating at normal incidence and in the fully tumbled condition. It was proposed, first, to develop a non-flowering fuel line. This was done by developing metallic, semi-metallic, and plastic composite fuel lines that are non-flowering and by reinforcing fuel lines with a damage-control system to make them non-flowering. The non-flowering fuel lines developed were made self-sealing by application of existing self-sealing bladder materials and of existing integral tank self-sealing materials to the inside, outside, or both sides of the fuel line. If necessary, new self-sealing systems were to be developed. Efficient sealing against a fuel line pressure of 35 psi was required and was achieved.

A hydraulic ram study of the impact of projectiles on fuel lines under pressure was made to determine if any unusual phenomena occur that require special consideration in the development of non-flowering and self-sealing fuel lines. High-speed films were taken to observe the projectile behavior while penetrating the fuel lines. Very high local pressure phenomena were observed.

In the work performed for preventing rupturing and flowering of metallic fuel lines, flexible ballistic nylon laminate and/or a foam was used to reduce the damage to pinhole size holes which were sealable by using systems like a precompressed fuel sensitive foam self-sealing concept. Non-flowering semi-metallic fuel lines were made of laminated aluminum foil. These were made effective against .30 and .50 caliber AP projectiles by protecting with flexible laminates bonded on the inside and outside of the line. Non-flowering plastic fuel lines were fabricated by using ballistic nylon cloth, polysulfide sealant, foam, and epoxy resin. Pinhole size holes were experienced when these lines were impacted by .30 caliber AP projectiles. Self-sealing was performed against .30 and .50 caliber AP projectiles by using fuel sensitive and precompressed foam.

Burst and collapse pressure tests were conducted with the laminated foil fuel lines and the plastic fuel lines both unprotected and protected.

All the work items mentioned above are reviewed in Section II of this report.

SECTION II

TECHNICAL DISCUSSION

The state-of-the-art technique for protecting conventional aluminum fuel lines is to wrap the lines with a self-sealing material similar to that used in self-sealing fuel cells or bladders. This technique often is less than satisfactory because the fuel line flowers when a fragment or projectile passes through it, and the flowering of the metal fuel line makes an open hole in the self-sealing material that does not seal. Furthermore, the high fuel line pressure in the line (≈35 psi) keeps the wound open and prevents the self-sealing system from acting.

Under Air Force contracts, Northrop has developed techniques to reduce or eliminate catastrophic rupturing of aircraft integral fuel tank walls when impacted by AP and API projectiles. These damage control systems prevent the flowering of the integral tank wall and allow the self-sealing systems to operate efficiently. One of the most successful self-sealing systems developed to date is the system using a precompressed and fuel sensitive foam for sealing in combination with a flexible ballistic nylon laminate as the damage control system. The ballistic nylon damage control system is essentially a high-tear-strength flexible laminate which prevents flowering of the integral metal tank wall.

The development of self-sealing systems for fuel lines presents two more drastic problems than the similar development for integral fuel tanks. First, because the fuel lines are so small in diameter, flowering caused by projectile passage becomes a major problem. In a large integral tank wall, one foot square or larger, the wall motion can relieve the effect of the flowering; the exit wall moves outward with the projectile and the hydraulic ram pressures, and this motion relieves the tendency to flower. However, the small diameter, 2- to 3-inch fuel line is essentially rigid to the impact of a projectile or fragment. Flowering is drastic and is not relieved by the motion of the metal fuel line wall. Second, the self-sealing must be more rapid and of higher strength for the fuel line than for an integral fuel tank. The fuel line operates at a fuel line pressure of about 35 psi. This pressure produces liquid flow that tends to keep any fragment or projectile wound open, and prevents self-sealing materials from closing the wound. The self-sealing systems must be able to resist the effect of the 35 psi in the fuel line.

In this work, Northrop has considered the exploratory development of a non-flowering self-sealing fuel line material for protecting fuel lines against .50 and .60 caliber AP projectiles penetrating at normal incidence, and .30 caliber AP projectiles penetrating in a tumbled condition. Initially, non-flowering fuel lines were developed. This was done either by the development of a metal, a semi-metallic, or a plastic composite fuel line that is non-flowering, or by reinforcing a metal, a semi-metallic, or a plastic fuel line with a damage control system to make it non-flowering. Then the non-flowering fuel line developed was made self-sealing by application of existing integral fuel tank self-sealing materials to the inside, outside, or both sides of the line. The approach to self-sealing against high pressure was three-fold: first, we used a damage control system that will hold the self-sealing material in the wound area; second, we used a pressurized system with a natural tendency to flow into the wound; and third, we used the fuel line pressure to help push the sealing material into the wound area.

A hydraulic ram effect study of the impact of projectiles on fuel lines under pressure was made to determine if any unusual phenomena are occurring that require special consideration in the development of non-flowering and self-sealing fuel lines.

A. DEVELOPMENT OF PROTECTION SYSTEMS FOR PREVENTING RUPTURING AND FLOWERING OF METALLIC FUEL LINES

1. Fuel Line Test Setup

Initially in the program, a fuel line test setup was fabricated. This was used in all fuel line ballistic tests. As shown in the diagram (Figure 1), this setup can be used in tests where either water or fuel is used as the circulating fluid. When fuel is used, the recycling system of the setup is used. The recycling of the fuel is performed with the help of a special fuel pump. This pump is explosion-proof and is set at 35 psig and 5 to 10 G.P.M. This will maintain the fuel under pressure while flowing through the fuel line before, during, and after impact. When using water as the circulating fluid, the fuel recycling system is shut off and the water system is used as shown in the diagram. The whole setup is mounted in such a way that it can be dismantled in a few minutes and transported in a compact state.

2. Ballistic Tests Performed with Unprotected and Protected (Damage Control System Only) Metal Fuel Lines

A series of tests was conducted where existing metal fuel lines, either unprotected or protected, were tested against .30 caliber AP and .50 caliber AP. A comparison was made of the degree of damage occurring with either the unprotected or protected metal fuel lines. All the lines had an I.D. of 2½ inches, a thickness of .028-inch, a length of 3 feet, and were 6061-T4 aluminum alloy (see Figure 2). Each line tested was mounted to the fuel line test setup (see Figure 1) with the water or fuel flowing at a 35 psi pressure inside the fuel line.

In the case of the protected metal fuel lines, the protection system used was either a 2-ply or 3-ply flexible ballistic nylon laminate and/or foam bonded on the outside of the line using 898 sealant (see configurations in Figures 3, 4, and 5). The systems were cured at 100°F for 4 hours. The flexible laminates were prefabricated using 2 or 3 layers of ballistic nylon cloth impregnated with 898 polysulfide sealant. A laminate using PRD-49 cloth was also used (see Figure 6). The laminates were used as damage control systems only and were not intended to self-seal the wounds. The immediate objective was to prevent or minimize rupturing or flowering of the metal line, and to determine whether the protective system would keep the damage low enough so that it could be sealed by a self-sealing system when impacted by small-arms projectiles (.30 and .50 caliber AP and .60 caliber ball).

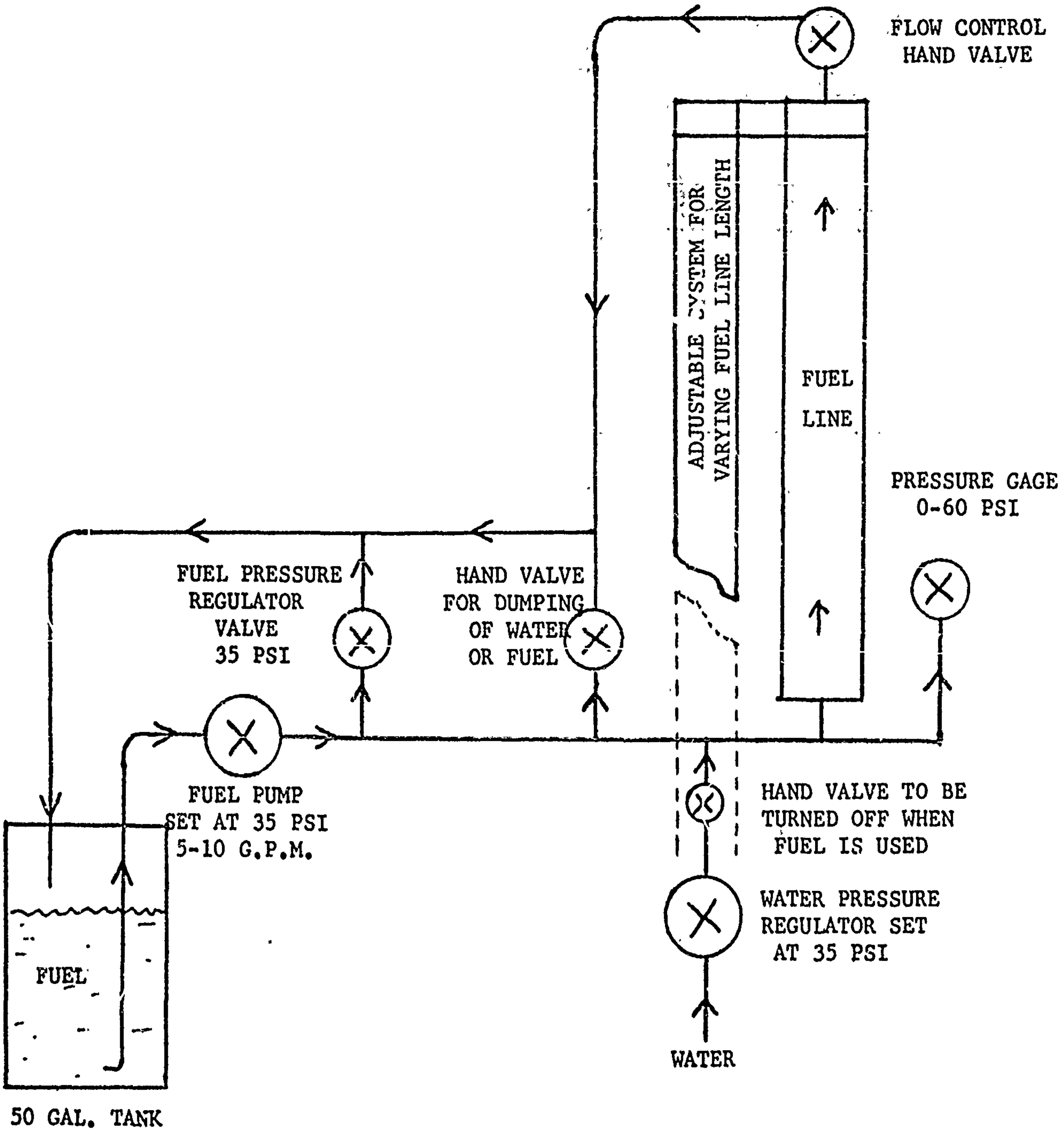


FIGURE 1. FUEL LINE TEST SETUP

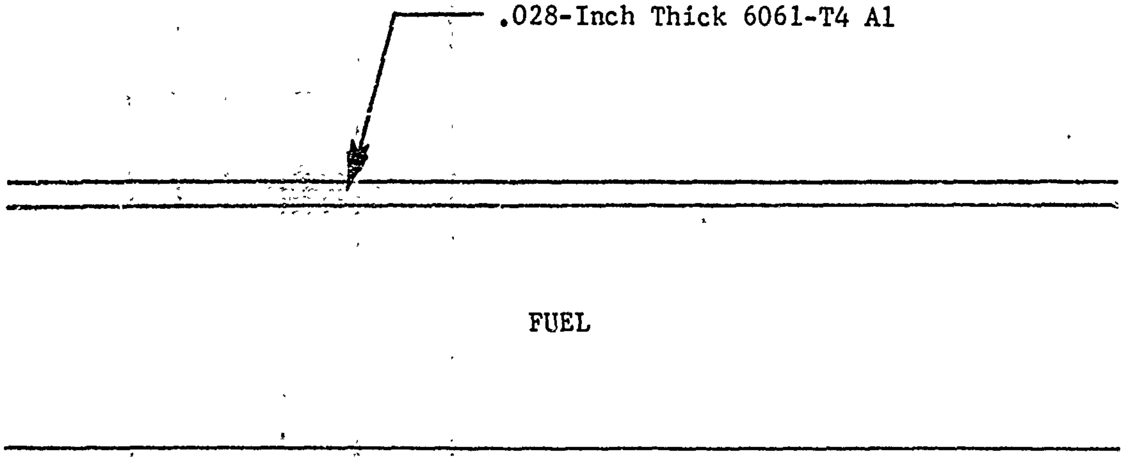


FIGURE 2. METAL FUEL LINE - LINE CONFIGURATION A

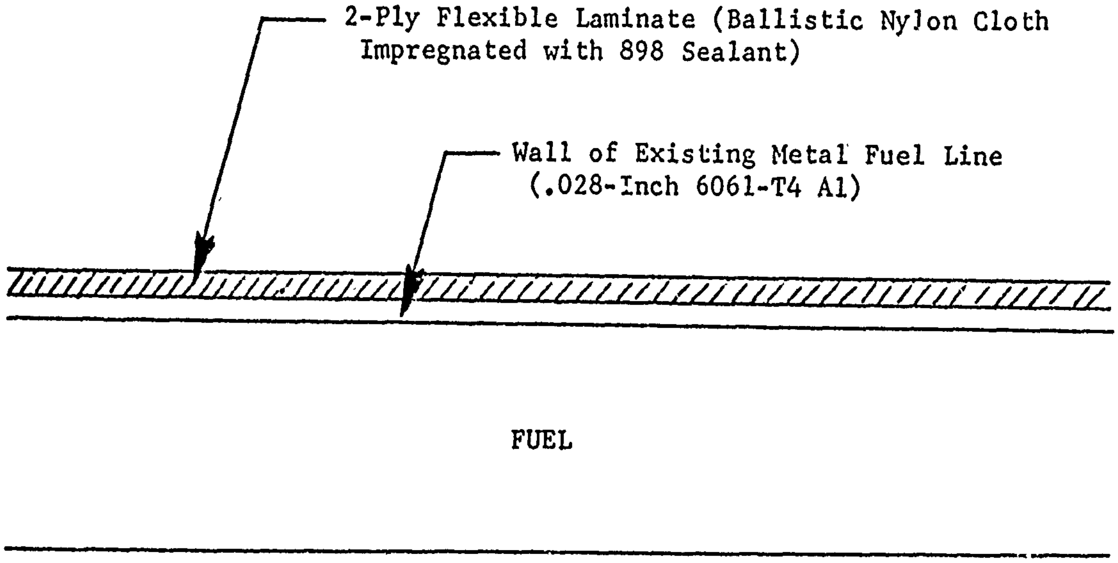


FIGURE 3. METAL FUEL LINE WITH DAMAGE CONTROL SYSTEM - FLEXIBLE LAMINATE - LINE CONFIGURATION B

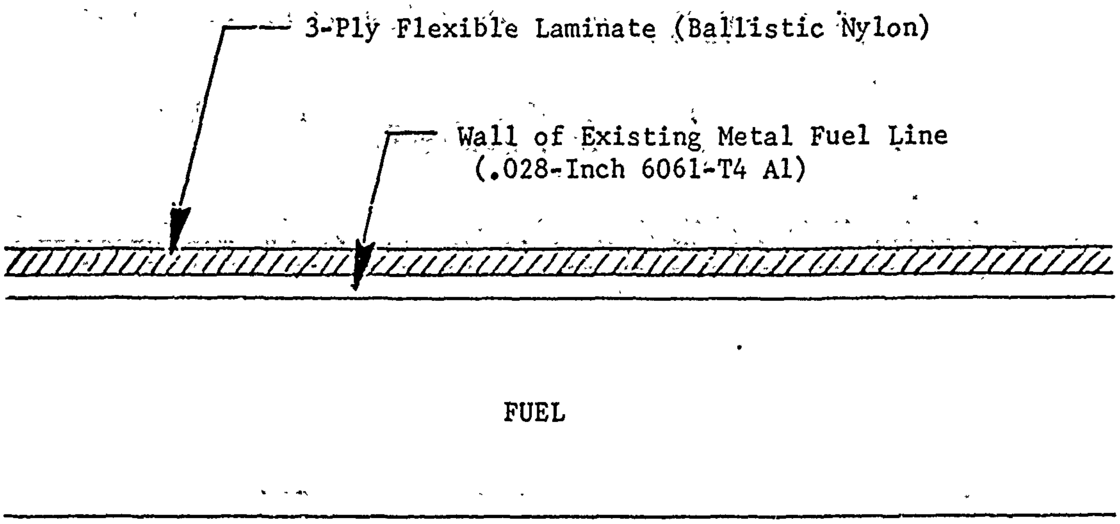


FIGURE 4. METAL FUEL LINE WITH DAMAGE CONTROL SYSTEM - FLEXIBLE LAMINATE - LINE CONFIGURATION C

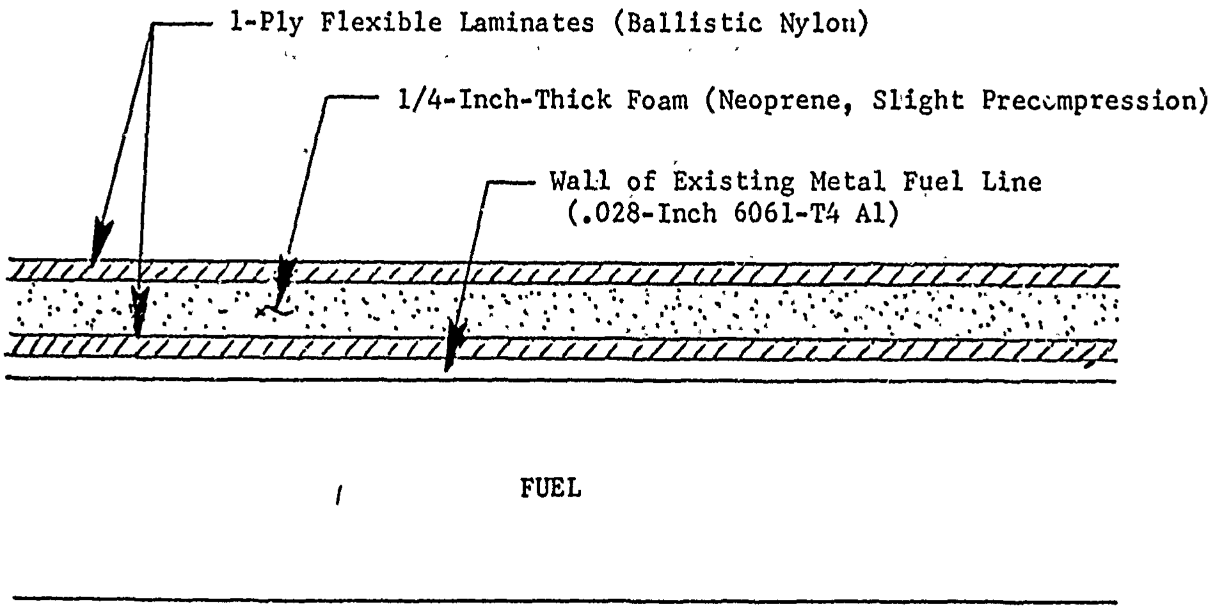


FIGURE 5. METAL FUEL LINE WITH DAMAGE CONTROL SYSTEM - FLEXIBLE LAMINATES AND FOAM - LINE CONFIGURATION D

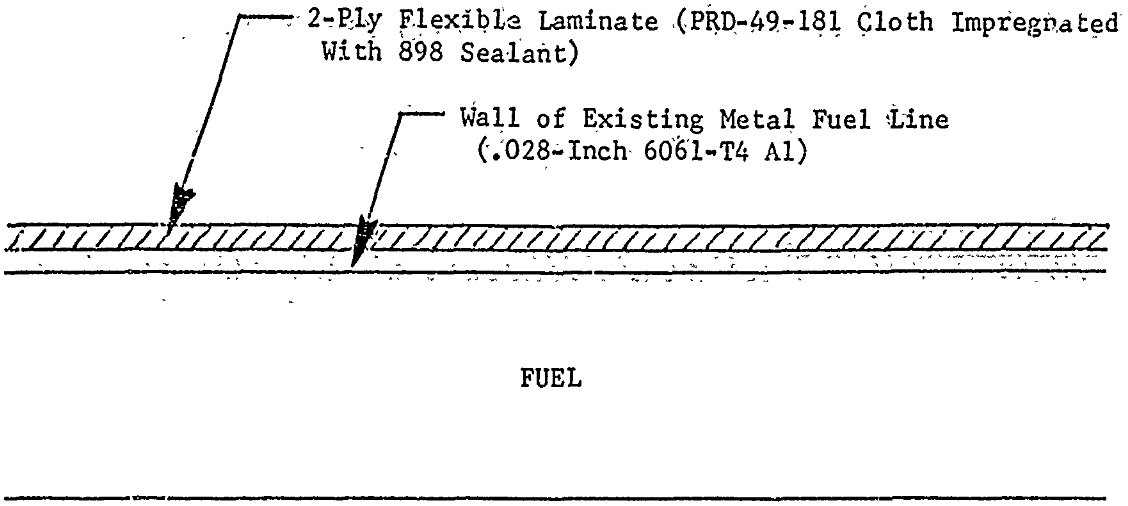


FIGURE 6. METAL FUEL LINE WITH DAMAGE CONTROL SYSTEM - FLEXIBLE LAMINATE - LINE CONFIGURATION E

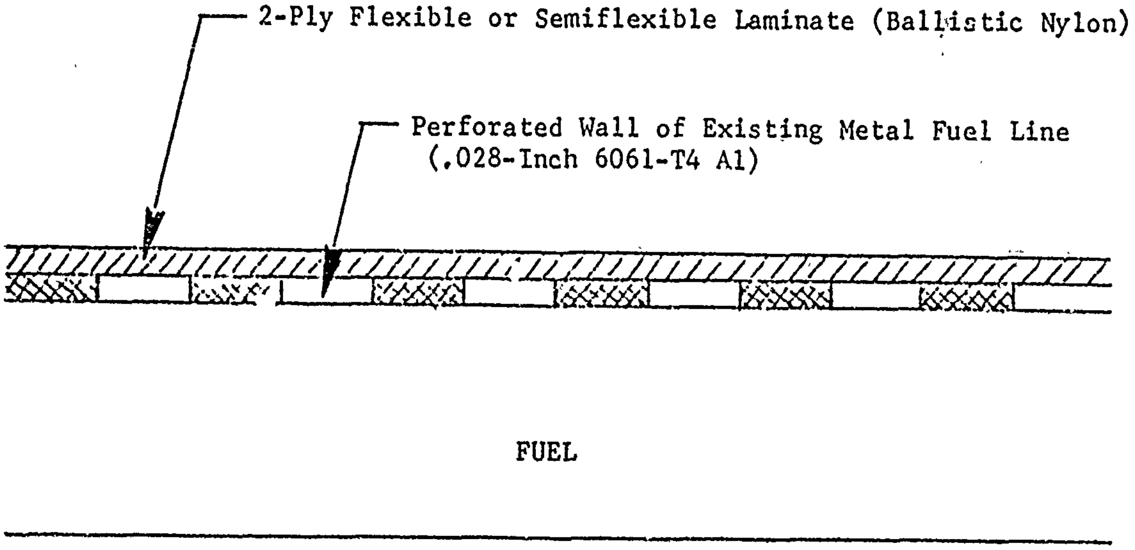


FIGURE 7. PERFORATED METAL FUEL LINE WITH PROTECTIVE SYSTEM - FLEXIBLE LAMINATE - LINE CONFIGURATION F

In addition to the existing metal fuel lines, either unprotected or protected, perforated metal fuel lines with protection systems (see Figures 7 and 8) were fabricated. The perforation lowered the weight of the line and minimized the flowering. The perforated metal line contained 3/8-inch diameter holes spaced approximately 3/16-inch apart. The procedure used in the fabrication of these perforated lines was (1) perforate a metal sheet (.028-inch thick, 6061-T4 Al) to the desired diameter holes, and (2) roll the perforated sheet into a 2½-inch I.D. line. The bonding agent used was either 898 polysulfide sealant or FM-123-2 (modified epoxy).

In this series of tests, .30 and .50 caliber AP projectiles impacted the lines either in a 90° or 45° angle of incidence (0° yaw) or in a tumbled condition. The results of impacts in the unprotected and protected lines are given in Table I and corresponding figures.

The line configurations denoted by a letter of the alphabet in each sketch of each figure are reflected by the same letter in Table I.

3. Performance of a Metal Self-Sealing Fuel Line

The sketch shown in Figure 15 describes the self-sealing concept which was evaluated. This system was used earlier (see Section A2 of this write-up) as a protection system to prevent flowering of the fuel line wall. With a slight modification, it can be used as a protection system and a self-sealing system. Incorporating a higher degree of precompression of the foam and a fuel sensitive foam (such as natural rubber foam), the system gave an effective fast seal against .30 caliber AP projectiles.

As shown in Figure 15, the flexible laminates and foam (¼-inch thick natural rubber foam) were bonded together to the metal line by using 898 polysulfide sealant. The completed self-sealing line was mounted to the fuel line test setup. The fuel (JP-4) recycling system of the setup was used and the line pressure was set at 35 psi. Upon impact, no loss of fuel was noticed and the line pressure dropped to 34 psi (as witnessed by a high-speed film) for a very short time before returning to the initial fuel flowing pressure of 35 psi. The degree of damage suffered by the metal self-sealing fuel line is shown in Figure 16. At the entry side the metal wall showed heavy inward flowering. This did not affect the self-sealing system materials inasmuch as sealing was obtained. In a further test, an identical self-sealing fuel line was fabricated and tested, this time against a .50 caliber AP projectile. The damage at the entry and exit sides was minor, but due to the heavy flowering of the metal wall at the exit side, a complete seal was not obtained. For more details on damage, see results in Table I.

B. DEVELOPMENT OF NON-FLOWERING SEMI-METALLIC FUEL LINES

In the development of semi-metallic fuel lines, a series of concepts was investigated. One of these concepts in particular, because of its promising aspects, was thoroughly evaluated during this program. This was the concept of a combination of laminated aluminum foil and flexible or semi-flexible laminates. A sketch of this concept configuration is given in Figure 17.

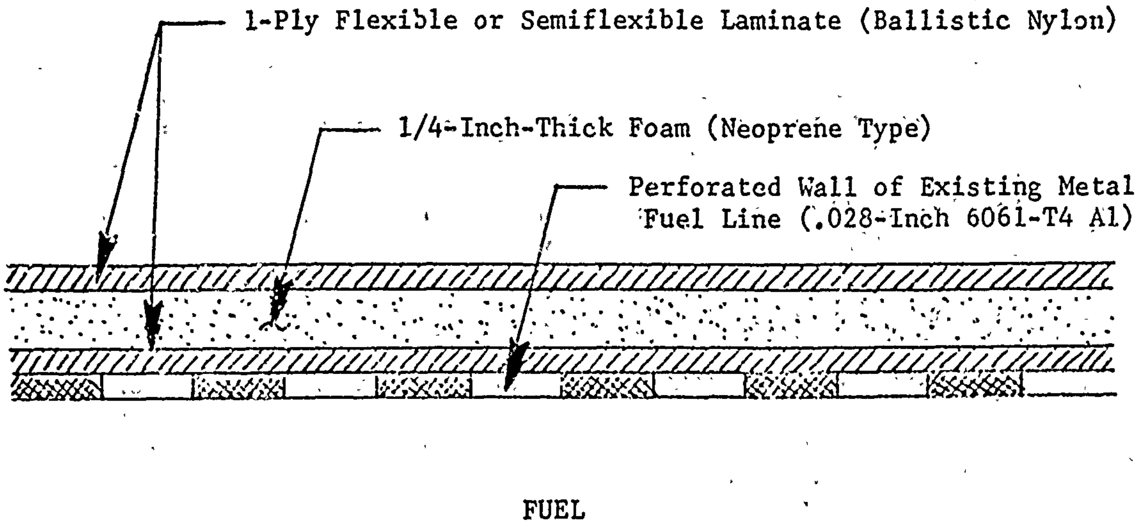


FIGURE 8. PERFORATED METAL FUEL LINE WITH PROTECTIVE SYSTEM - FLEXIBLE LAMINATES AND FOAM - LINE CONFIGURATION G

TABLE I
IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED METAL FUEL LINES

	PROTECTIVE SYS.USED		WEIGHT ADDED			BALLISTIC TESTS					
LINE CONF	DAMAGE CONTROL NON-SELF-SEALING	SELF-SEALING	TO BARE LINE PER FT^2 IN LBS.	TO BARE LINE PER LINEAR FT. ID=2¼"IN LBS	THICKNESS ADDED IN INCHES	PROJECTILE USED: CAL.AP	CONDITIONS OF PROJECTILE IMPACT	INITIAL WATER OR FUEL PRESS. IN LINE (PSI)	FUEL OR WATER PRESS.RECORDED AFTER IMPACT (PSI)	SEALING ACTION	REMARKS
A	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, grazed line	35	5	- -	The damage at the entry was a 3/8" dia.hole. At the exit, damage was heavy. (Figs. 9 & 10, Line 5:18.72-I)
A	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line. A 100" thick Al plate (7075-T6) was placed in front of line (½" away)to simulate penetration of an a/c skin structure before hitting fuel line.	35	6	- -	Damage at entry was a ¼" dia. hole & at exit damage was ½" x 3/8" hole with a 1½" long crack across the hole. (Figs. 9 & 10, Line 5:19.72-I)
A	None	None	None	None	0	.30	45° angle of incidence, 0° yaw, middle of line.	35	0	- -	A 3/8" dia. hole with no cracks occurred at the entry. At the exit,the damage was a 3/8" hole with minor rupturing around the hole. Leakage was heavy. (Figs. 9 & 10, Line 5.19.72-II)
A	None	None	None	None	0	.30	90° angle of incidence,slight tumbling,middle of line.	35	0	- -	Projectile left a ½" x ¼" hole at entry & a 2" x 1½" hole with heavy outward flowering at exit. The fluid loss was heavy. (Figs. 9 & 10, Line 5:19.72-III)
A	None	None	None	None	0	.50	90° angle of incidence,middle of line.	35	0	- -	Damage at entry was a ½" dia. hole with slight cracking around hole. At exit,damage was a 1" x 2½" long hole with heavy outward flowering. The fluid loss was heavy. (Figs. 9 & 10, Line 5.22.72-II)
A	None	None	None	None	0	.30	45° angle of incidence,0° yaw,middle of line,projectile hit line fitting.	35	0	- -	Projectile penetrated fitting at entry & exited fitting at exit. This provoked heavy rupturing of line & fitting. (Figs. 11 & 12, Line 5.23.72-I)

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED METAL FUEL LINES (Continued)

A	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line.	35	8	- -	At entry & exit, 3/8" dia. holes occurred with outward flowering at exit & inward flowering at entry. No outward bulging around the circumference of line.
B	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, grazed line.	35	19	- -	The damage in the laminate at entry & exit was minor. The water loss was small. (Fig. 9, Line 5.18.72-II)
B	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line. A .100" thick Al plate (7075-T6) was placed in front of line (½" away) to simulate penetration of an a/c skin structure before hitting the fuel line.	35	20	- -	The damage to laminate at entry & exit was very small. At exit, the metal line was slightly distorted underneath the laminate. Water leakage was small.
B	Yes	None	.34	.21	1/16	.30	90° angle of incidence, tumbling, middle of line.	35	19	- -	Bullet penetrated line in a slightly tumbled condition, leaving a 3/8" sealable slit in laminate at entry & a 5/8" long slit in laminate at exit. Small water leakage.
B	Yes	None	.34	.21	1/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	18	- -	The damage to laminate was minor. At entry, a 1/8" hole & at exit a ½" hole occurred with no tearing of laminate. Water leakage was small. (Figs. 9 & 10, Line 5.22.72-I)
B	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	20	- -	Entry side showed small hole & a 1/8" dia. hole at exit side. Inward flowering of metal at entry occurred, but small hole in laminate would have allowed a seal in the presence of a self-sealing system. At exit, the flowering was minor & sealing could have been achieved here too. (Figure 13)

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED METAL FUEL LINES (Continued)

C	Yes	None	.51	.30	3/32	.30	90° angle of incidence,0° yaw,middle of line.	35	25	--	Entry side showed small hole & 1/8" dia.hole at exit side. Inward & outward flowering occurred at entry & exit sides respectively. In this shot, the outward flowering at exit side was smaller than in the case of the 2-ply laminate protection.
D	Yes	None	.60	.36	5/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	30	--	The flexible laminate & foam showed promising results. The impacting .30 cal.AP projectile left very small holes at the entry & exit sides of the line. The inward petalling of the metal line was minor at the entry side. (Figure 14)
D	Yes	None	.60	.36	5/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	26	--	Results were similar to line configuration D above. The only difference was that the line pressure dropped to 26 psi instead of 30 psi.
E	Yes	None	.38	.23	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	10	--	The entry side showed a 3/8" dia.hole & inward flowering. At the exit, a 3/4" long slit occurred with some tearing of the PRD-49 cloth. Damage was more severe than with ballistic nylon laminate.
F	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	21	--	Damage at the entry & exit sides of line was minor. No inward or outward flowering occurred. A weight reduction of the line results from the removal of metal due to perforations in the line. The weight reduction is approx. .20 lb/ft^2.
G	Yes	None	.60	.36	5/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	29	--	Damage at entry & exit sides was minor. No inward or outward flowering. Similarly as above in F, a weight reduction can be taken into account due to perforations in the line. The weight reduction is approx. .20 lb/ft^2.

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED METAL FUEL LINES (Continued)

H	Yes	Yes	.66	.40	5/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	35	Immediate	Minor damage was noticed at entry & exit sides of line. Upon impact, no loss of fuel occurred, the line pressure dropped to 34 psi (as witnessed by a high speed film) for a very short time before returning to initial fuel flowing pressure of 35 psi. (Figure 16)
H	Yes	Yes	.66	.40	5/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	29	Immediate seal at entry side but did not seal completely at exit side	Damage at entry and exit sides was minor. At entry side the metal wall showed heavy inward flowering. At the exit side the degree of outward flowering of the metal wall interfered to some extent with the self-sealing mechanism.

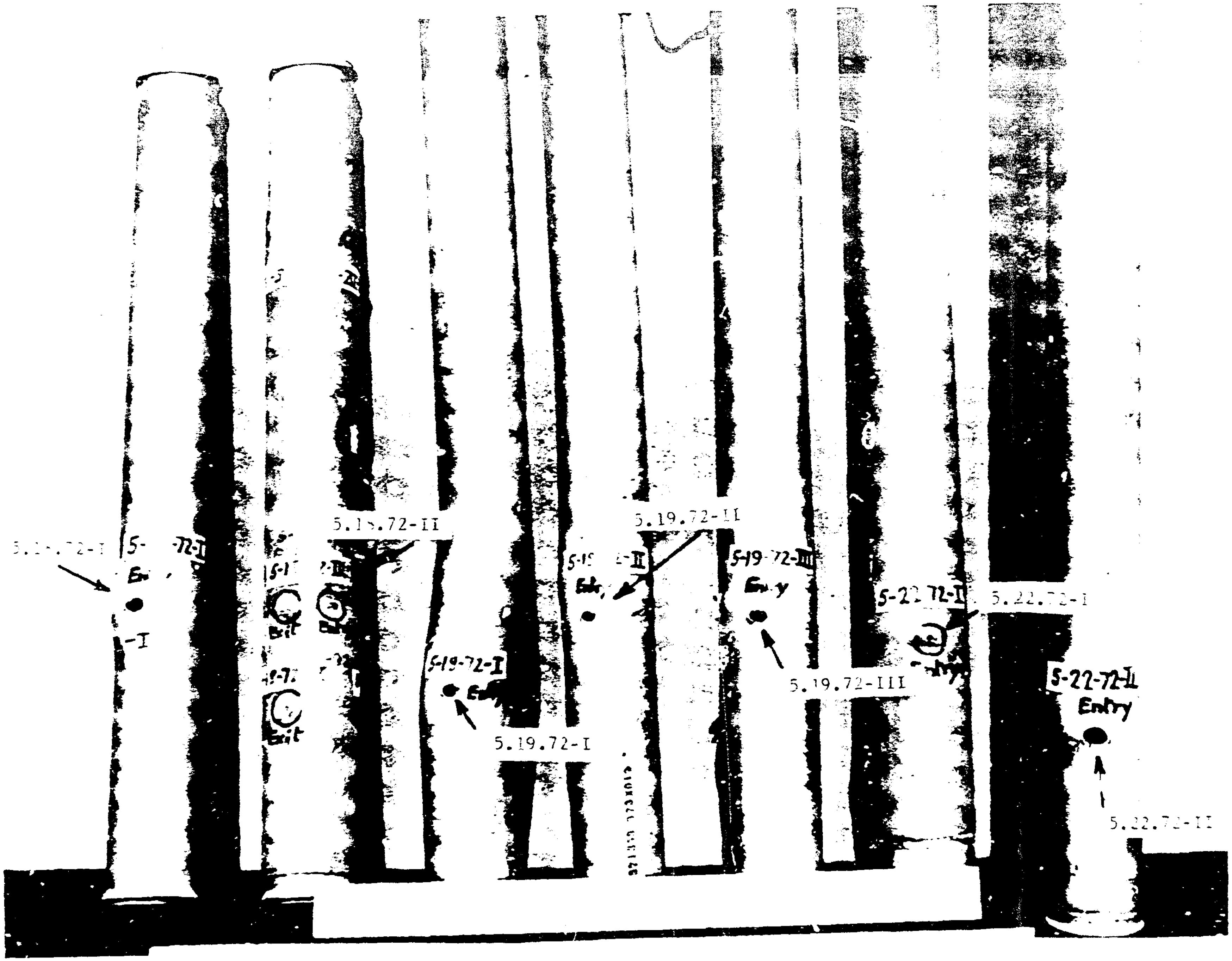


FIGURE 9. IMPACTS IN PROTECTED AND UNPROTECTED LINES (35 LB. LINE PRESSURE) - LINE ENTRY SI

FIGURE 10. IMPACTS IN PROTECTED AND UNPROTECTED LINES (35 LB. LINE PRESSURE) - LINE EXIT SIDE

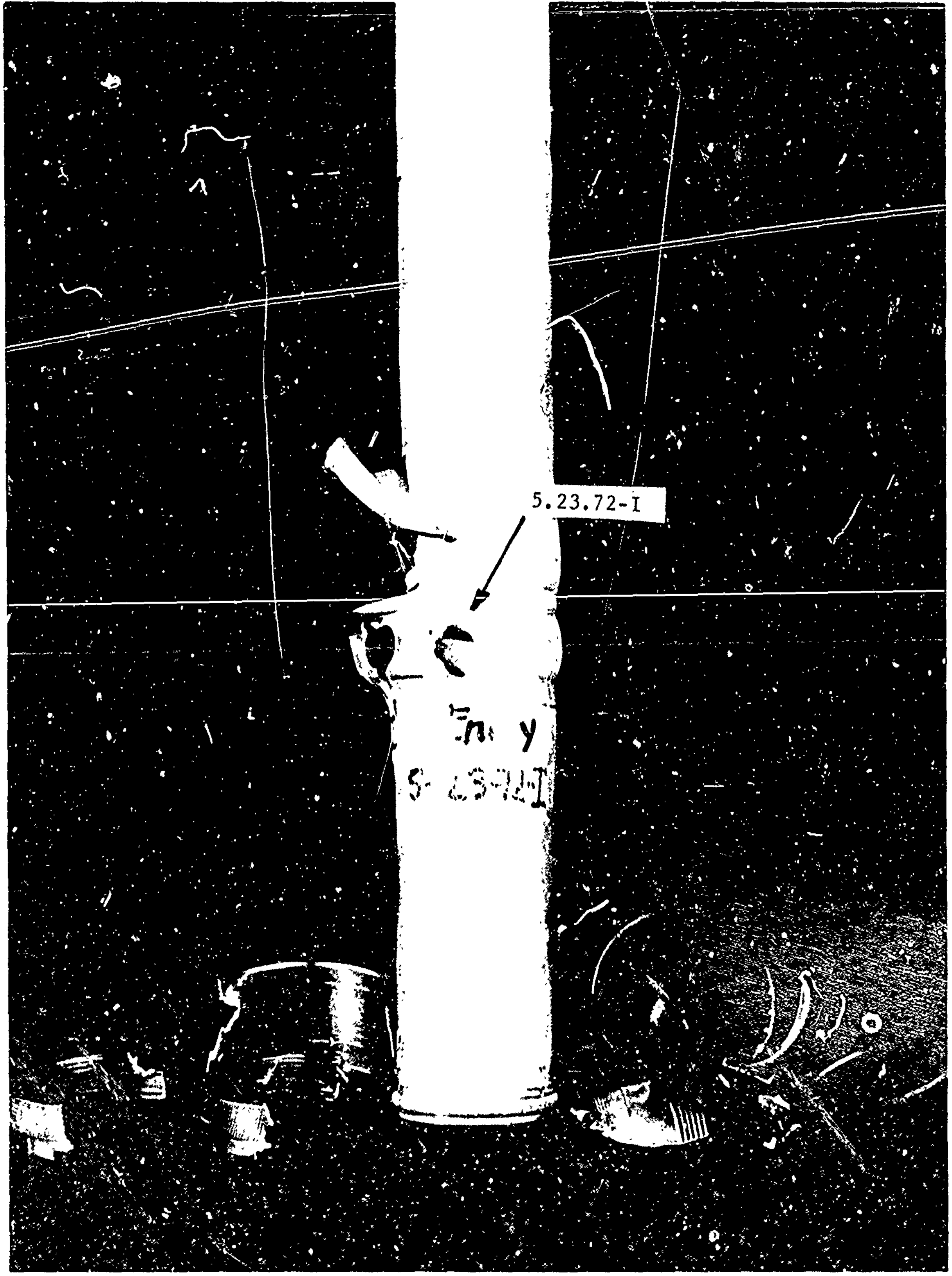


FIGURE 11. METAL FUEL LINE - BULLET HIT FITTING - ENTRY SIDE

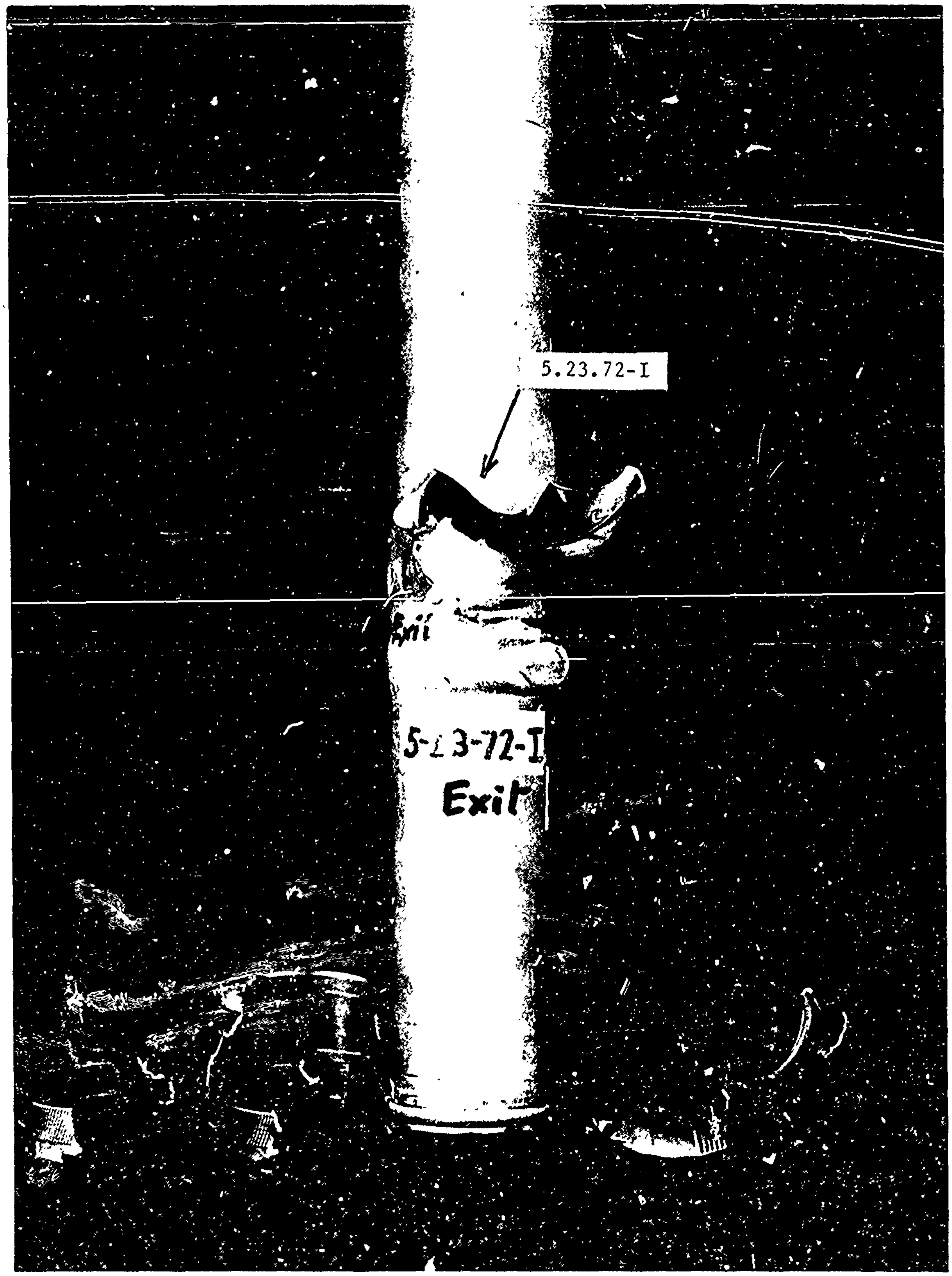
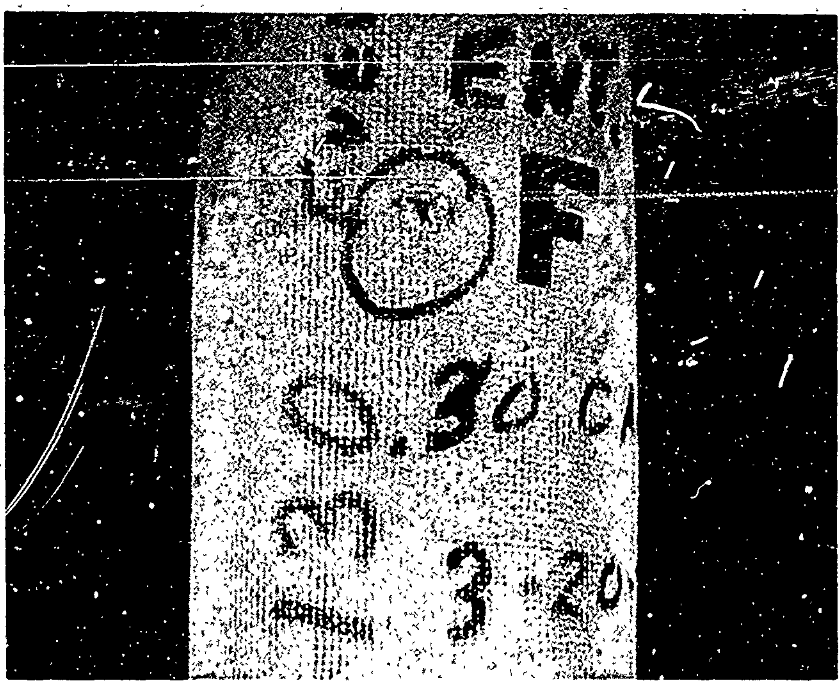
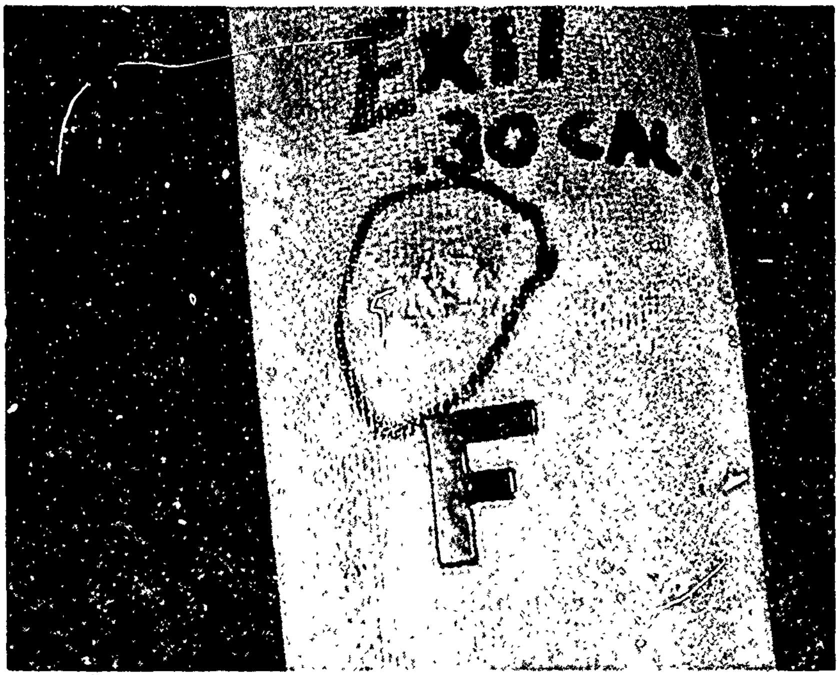


FIGURE 12. METAL FUEL LINE - BULLET HIT FITTING - EXIT SIDE

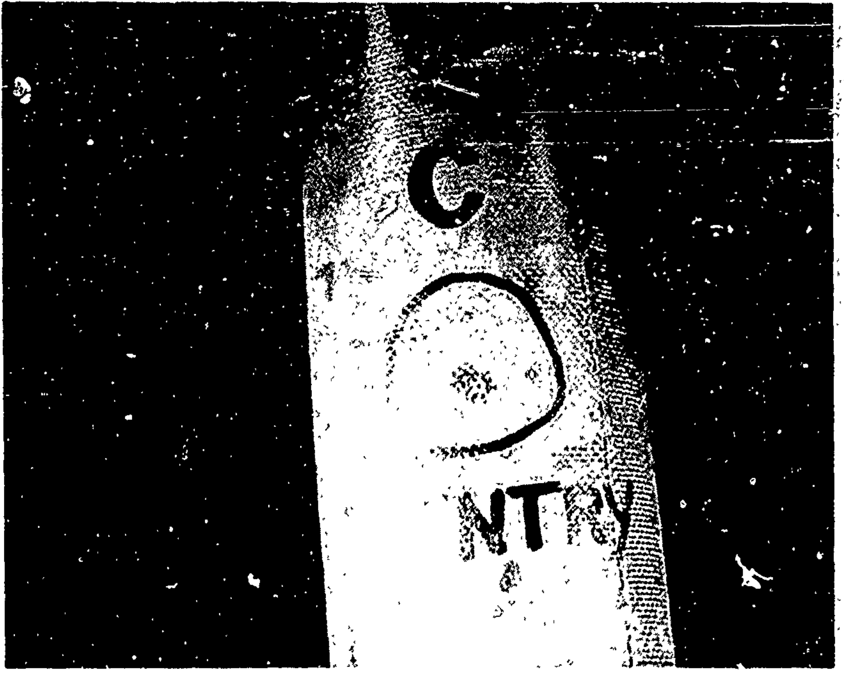


Entry Side



Exit Side

FIGURE 13. METAL FUEL LINE PROTECTED WITH
2-PLY FLEXIBLE LAMINATE



Entry Side

Exit Side

FIGURE 14. METAL FUEL LINE PROTECTED WITH FLEXIBLE LAMINATE AND FOAM

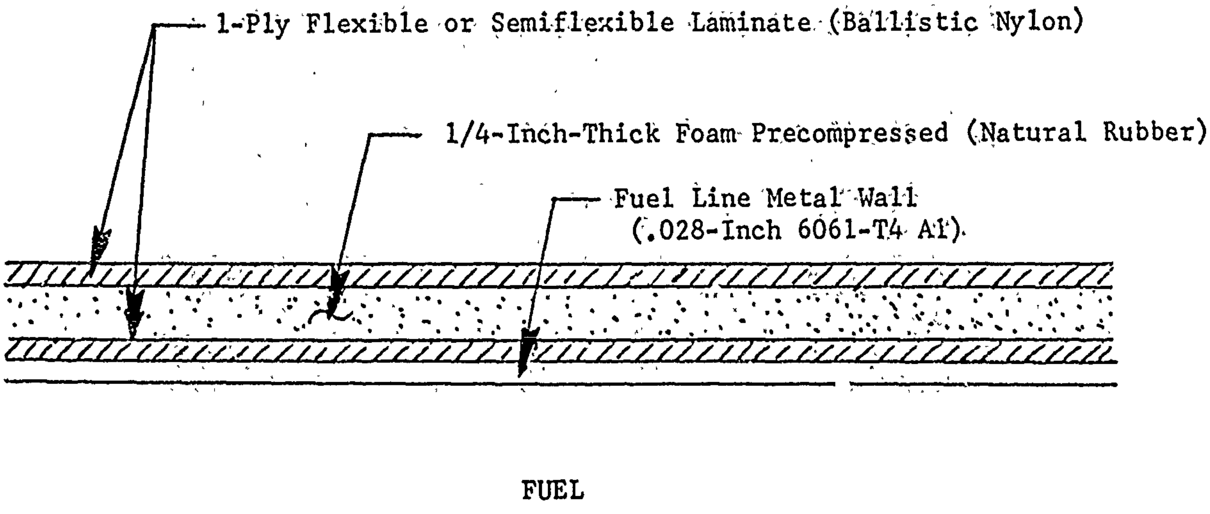
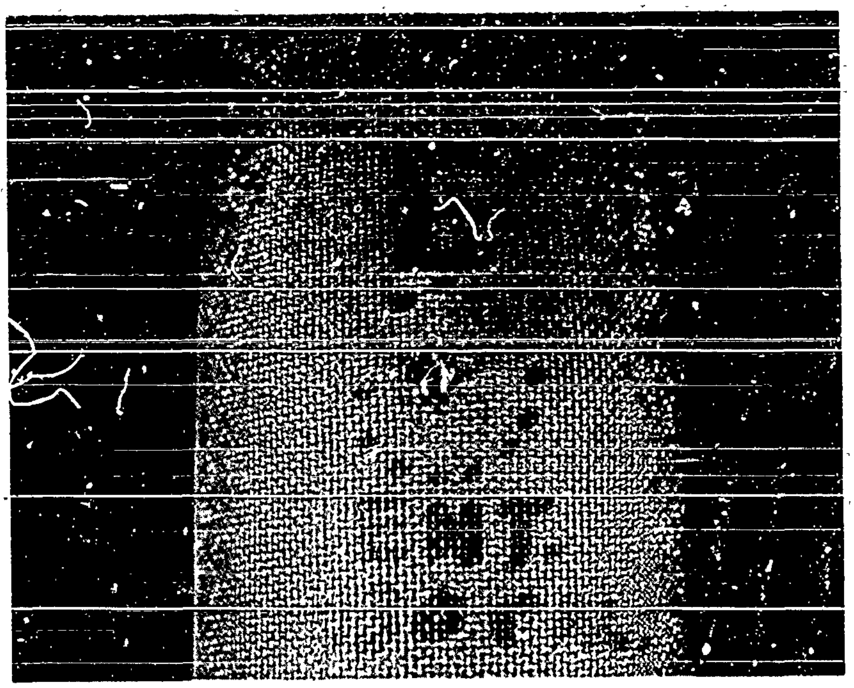
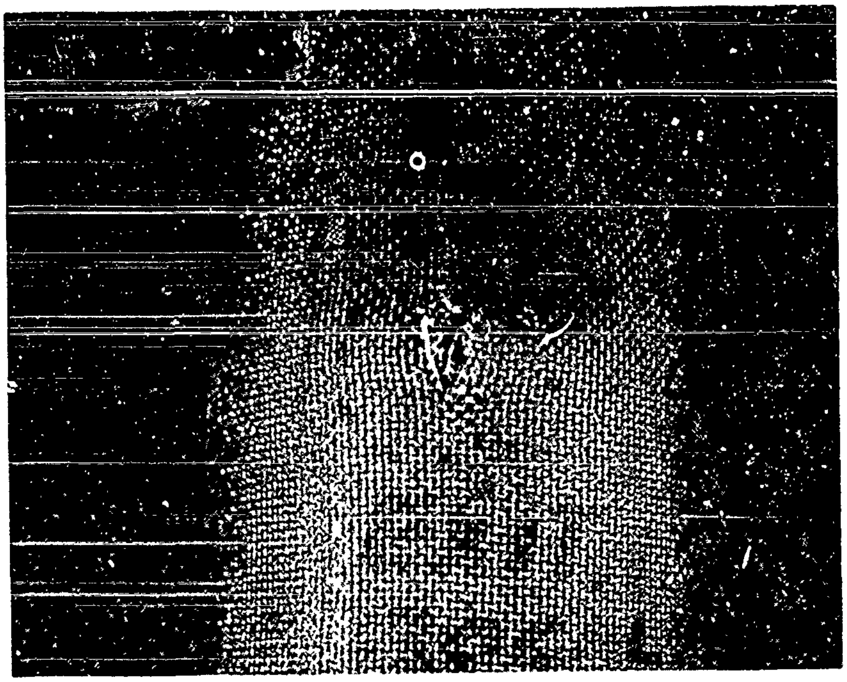


FIGURE 15. METAL SELF-SEALING FUEL LINE - LINE CONFIGURATION H



Entry Side



Exit Side

FIGURE 16. TEST RESULTS OF THE METAL SELF-SEALING FUEL LINE

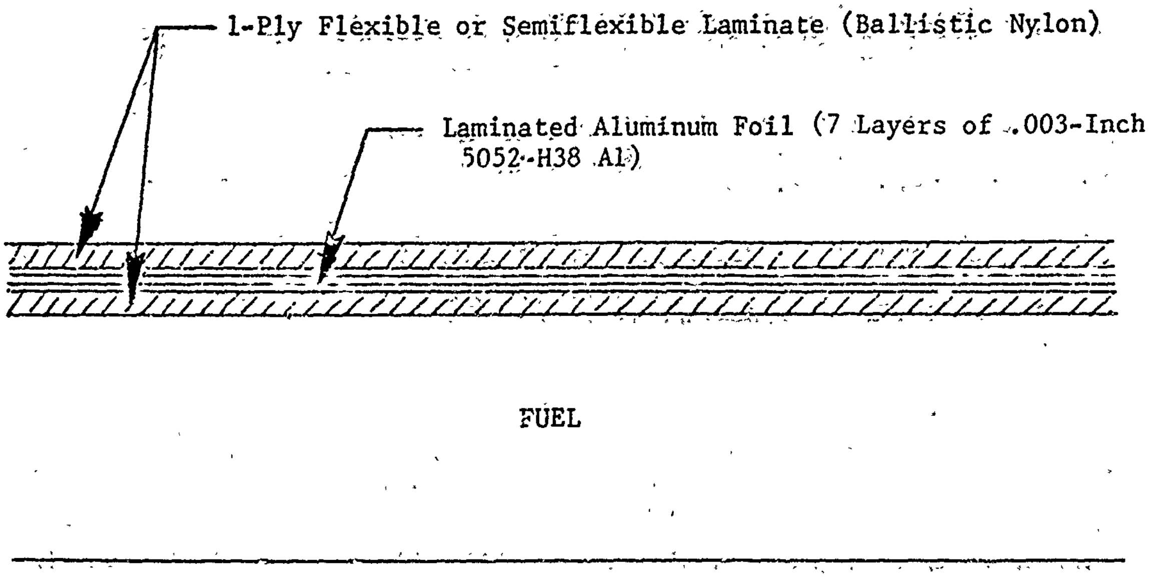


FIGURE 17. NON-FLOWERING SEMI-METALLIC FUEL LINE CONCEPT - LINE CONFIGURATION J

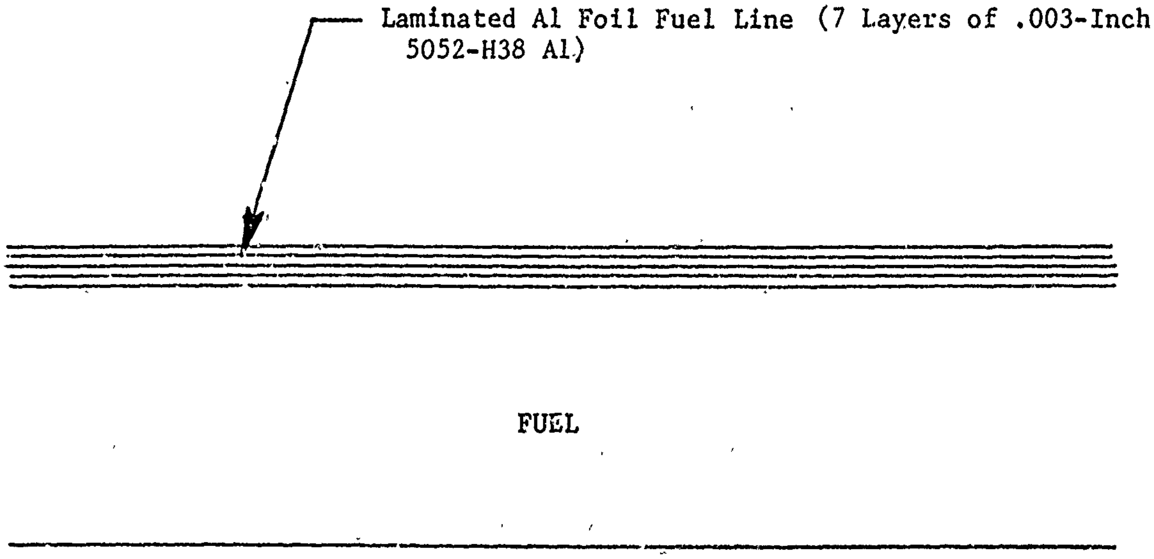


FIGURE 18. LAMINATED ALUMINUM FOIL FUEL LINE - LINE CONFIGURATION I

1. Preparation of Laminated Aluminum Foil Fuel Lines Unprotected and Protected (Non-Self-Sealing) and Ballistic Tests

Eight laminated metal fuel lines, either protected or unprotected, were fabricated and ballistically tested against .30 caliber AP projectiles. The metals used were as follows:

a. 5052-H38 - .003-inch thick (7 layers)
b. 1100-0 - .004-inch thick (5 layers)
c. 5052-H38 - .004-inch thick (5 layers)
d. 1100-0 - .002-inch thick (10 layers)

The total thickness of the laminated metal fuel line walls is approximately .030-inch. The length of the lines is 25 inches and the I.D. is 2½ inches. The bonding agent used to bond the thin metal sheets is 898 polysulfide sealant. With each metal type and thickness described above, a protected and unprotected laminated metal fuel line was prepared. The protected fuel lines contain a 1-ply flexible ballistic nylon laminate on the outside and inside of the line as shown in the sketch of the concept (Figure 17).

a. Fabrication Methods Used for the Laminated Metal Fuel Lines

(1) Method for the Unprotected Laminated Metal Fuel Lines

(a) A 32-inch long aluminum pipe having an O.D. of 2½ inches and a wall thickness of 5/16-inch is used as a mold.

(b) In the first step, the mold is wrapped with a layer of non-porous Teflon impregnated glass cloth to act as a mold releasing agent.

(c) For each laminated metal fuel line to be fabricated, the corresponding metal sheet is cut to a length to give the exact number of layers when finally rolled onto the pipe mold.

(d) The cut metal sheet is then layed out on a table and a thin layer of polysulfide 898 sealant is spread evenly on the surface of the sheet. The mold (aluminum pipe) with the releasing agent is then placed at one end of the 898 sealant covered metal sheet. The metal sheet is rolled carefully and evenly around the pipe mold.

(e) After the rolling of the metal sheet is completed, a layer of non-porous Teflon impregnated glass cloth is placed around the laminated line. A plastic tape is then wound tightly and evenly around the line to apply pressure to make good contact between each metal layer and obtain a good bond.

(f) Finally, the mold containing the metal sheet under pressure is placed in an oven at 180F for approximately 1½ hours to cure the polysulfide adhesive. Before removing the mold from the oven, the temperature inside the oven is lowered to room temperature. This cooling is necessary for self-sealing systems containing foam and is used as a normal precaution. Next, the plastic tape and mold release (Teflon cloth) wound around the line are removed and the completed unprotected line is separated from the mold.

(2) Method for the Protected Non-Self-Sealing Laminated Metal Fuel Lines

For this method, steps (a) and (b) are the same as in the above method. In step (c) for this method, a layer of ballistic nylon cloth is cut to size to give a 1-ply laminate bonded inside the line. The cut ballistic nylon cloth is layed out on a table and is impregnated with 898 sealant material. The impregnated nylon is then rolled carefully and evenly around the mold to obtain a slight overlap where the two nylon cloth edges meet. Step (d) is similar to step (c) in the above method. Step (e) is also similar to step (d) above, with the exception that here the mold containing the 1-ply wet laminate is placed at one end of the 898 sealant covered metal sheet. The metal is rolled carefully and evenly around the wet laminate covered mold. Step (f) uses the same procedures as step (e) above, with the exception that before applying the non-porous Teflon impregnated glass cloth around the laminated metal line, a wet (898 impregnated sealant) ballistic nylon cloth layer is rolled around the laminated line to obtain a 1-ply flexible laminate bonded on the outside of the laminated metal line. At this point, the Teflon impregnated glass cloth is placed around the wet laminate covered laminated line and the remainder of the fabrication method is then similar to the above method for unprotected laminated metal fuel lines.

b. Ballistic Tests

In these tests, the fuel line test setup described above in Section A1 was used. For each test the protected or unprotected laminated metal fuel line was mounted to the fuel line test setup. The water circulating system of the test setup was used in the tests with the water flow pressure set at 35 psi. The gunfiring test was performed using the rifle with a 1-turn-per-10-inches rifling. The projectile (.30 caliber AP) hit the line in a 90° angle of incidence and 0° yaw. In the tests, the eight laminated metal fuel lines were identified as follows:

A1 Unprotected Line (5052-H38 Al - .003-inch thick - 7 layers) - Figure 18
A2 Protected Line (5052-H38 Al - .003-inch thick - 7 layers) - Figure 17
B1 Unprotected Line (1100-0 Al - .004-inch thick - 5 layers) - Figure 19
B2 Protected Line (1100-0 Al - .004-inch thick - 5 layers) - Figure 20
C1 Unprotected Line (5052-H38 Al - .004-inch thick - 5 layers) - Figure 21
C2 Protected Line (5052-H38 Al - .004-inch thick - 5 layers) - Figure 22
D1 Unprotected Line (1100-0 Al - .002-inch thick - 10 layers) - Figure 23
D2 Protected Line (1100-0 Al - .002-inch thick - 10 layers) - Figure 24

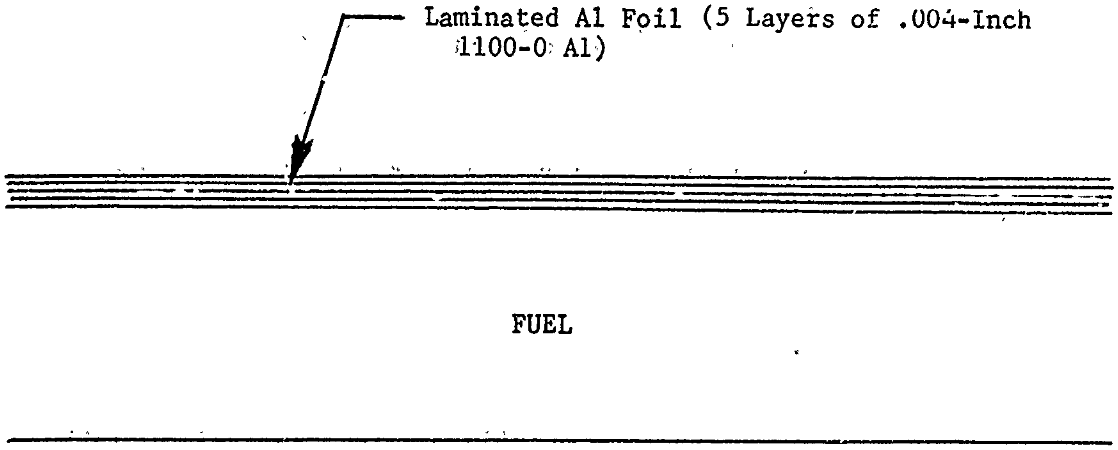


FIGURE 19. LAMINATED ALUMINUM FOIL FUEL LINE - LINE CONFIGURATION K

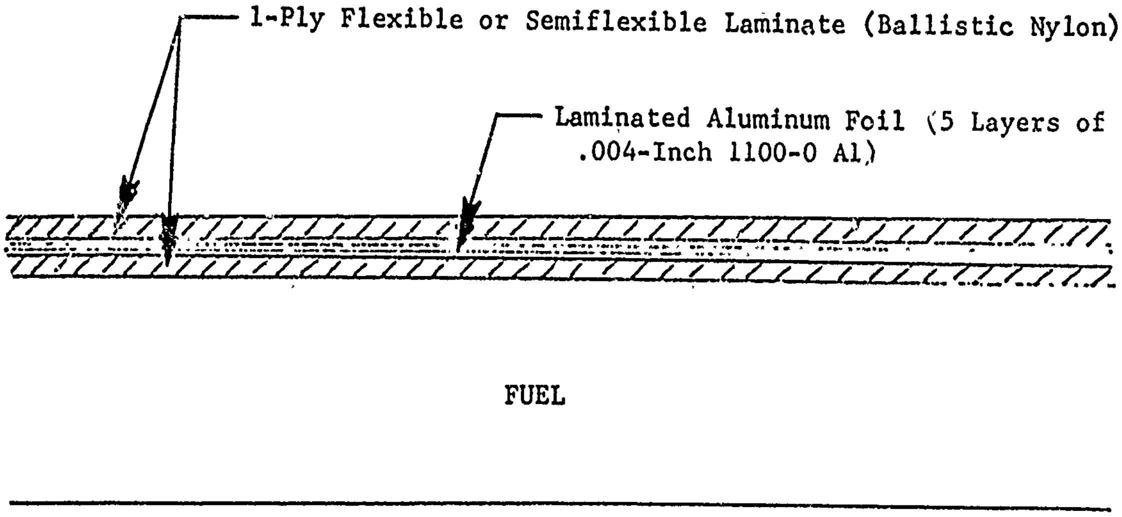


FIGURE 20. NON-FLOWERING SEMI-METALLIC FUEL LINE CONCEPT - LINE CONFIGURATION L

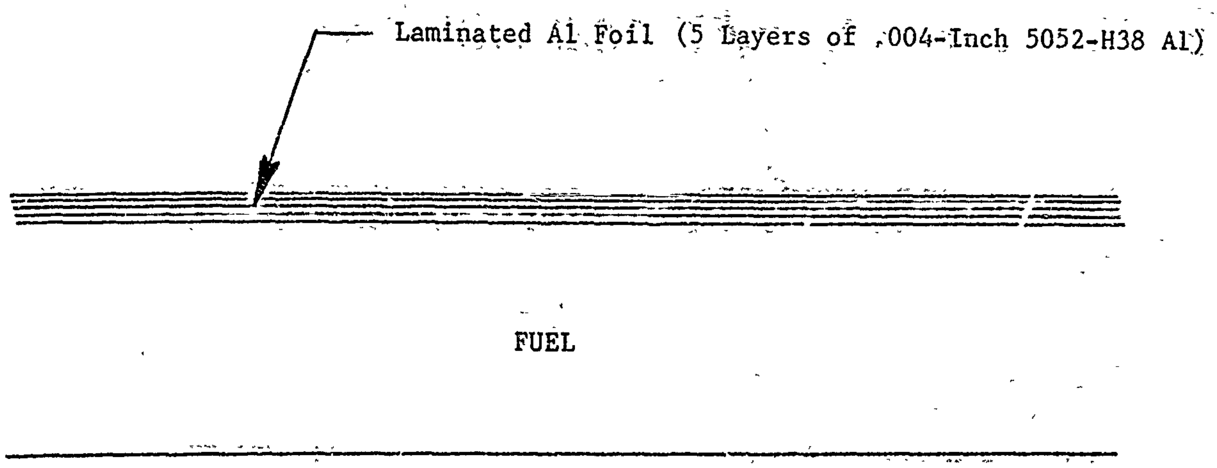


FIGURE 21. LAMINATED ALUMINUM FOIL FUEL LINE - LINE CONFIGURATION M

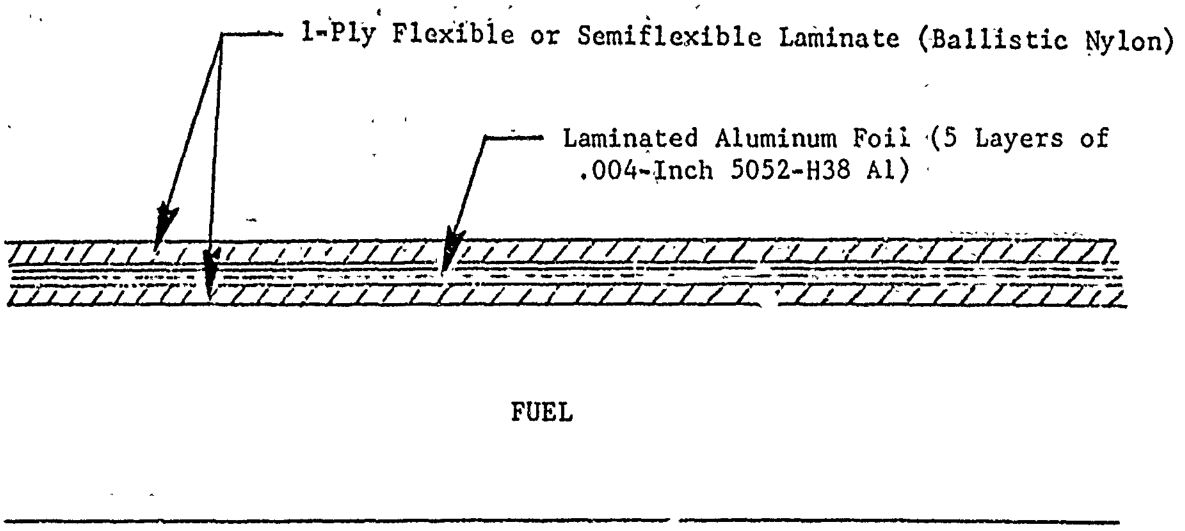


FIGURE 22. NON-FLOWERING SEMI-METALLIC FUEL LINE CONCEPT - LINE CONFIGURATION N

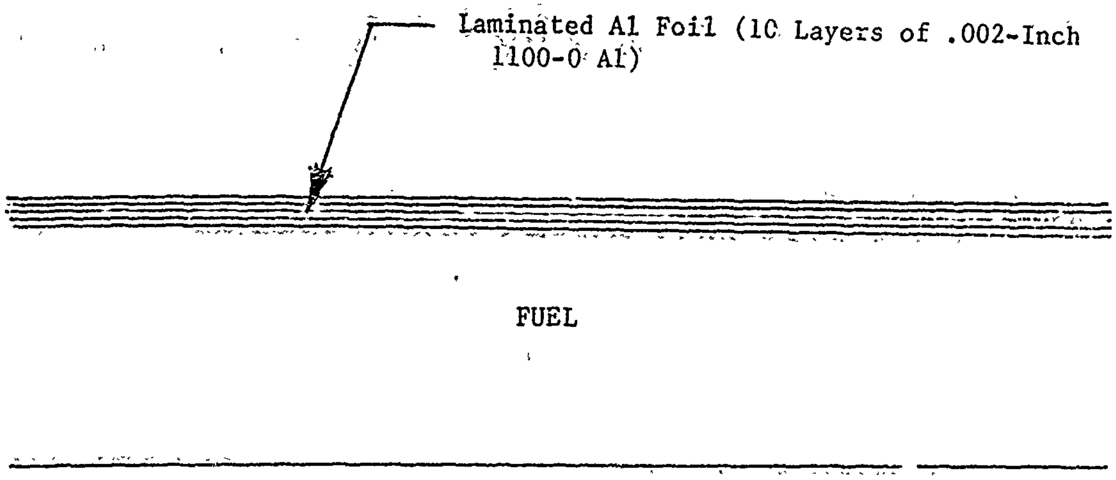


FIGURE 23. LAMINATED ALUMINUM FOIL FUEL LINES - LINE CONFIGURATION O

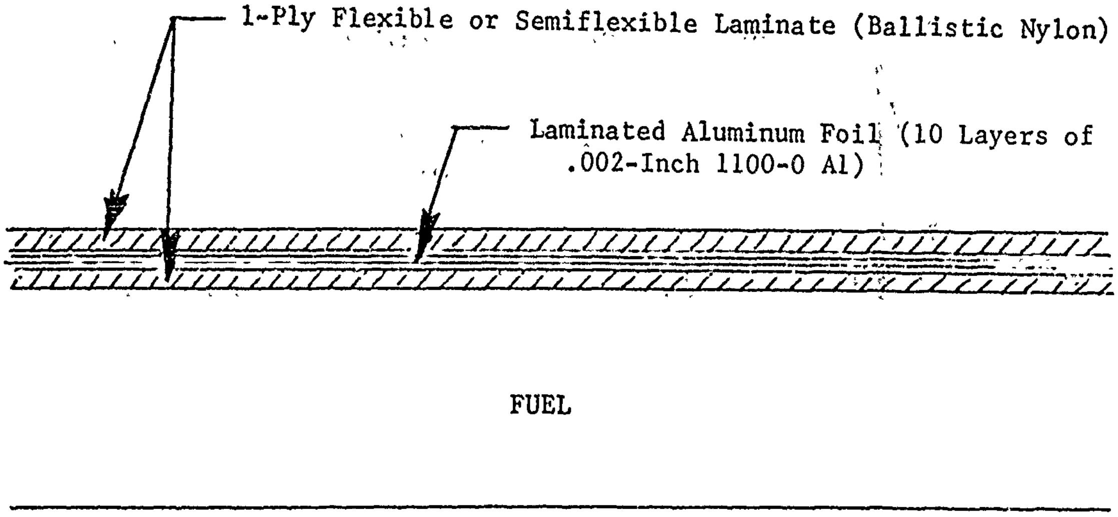


FIGURE 24. NON-FLOWERING SEMI-METALLIC FUEL LINE CONCEPT - LINE CONFIGURATION P

Test Results

A1 Line (Unprotected). At the entrance (see Figure 25) a ½-inch diameter hole occurred with outward and inward flowering. A 4-inch long longitudinal crack across the impact hole occurred. At the exit (see Figure 26) a 5/8-inch diameter hole was made by the exiting projectile. Only outward flowering occurred and a 3-inch long longitudinal crack across the hole occurred. The water flow pressure through the line dropped from 35 psi down to 12 psi.

A2 Line (Protected). In comparison, this protected line showed very promising results. At the entry (Figure 25) and exit (Figure 26) pinhole size holes were noted. No apparent cracking or flowering of the laminated metal line occurred. The flexible laminate on the inside and outside did not show any tear damage. The water flow pressure dropped from 35 psi down to 32 psi only.

B1 Line (Unprotected). In this test, catastrophic rupturing occurred at entry (Figure 27) and exit (Figure 28) and particularly at the exit. The line was almost cut in two and the water flow pressure dropped from 35 psi down to 0 psi.

B2 Line (Protected). A drastic difference in damage was observed in this shot. The 1-ply flexible laminate on the inside and outside of the line kept the damage to pinhole size holes at entry (Figure 27) and exit (Figure 28). Small cracking occurred in the laminated metal line underneath the laminate. No flowering of the metal line was noted. The water flow pressure dropped from 35 psi down to 30 psi.

C1 Line (Unprotected). The pattern of damage occurring with this line was very similar to the one with line A1 (Figures 29 and 30). However, the damage here was a little more extensive. The water flow pressure dropped from 35 psi down to 10 psi.

C2 Line (Protected). This line showed a pinhole size hole at the entrance (Figure 29) with no cracking of the laminated metal and no flowering. At the exit (Figure 30) the flexible laminate on the inside of the line showed a small hole and no inward flowering of the laminated metal line. The flexible laminate on the outside of the line showed a ¼-inch hole and outward flowering of the metal line. No cracking of the laminated line occurred. The water flow pressure dropped from 35 psi down to 22 psi.

D2 Line (Unprotected). The damage was still severe (Figures 31 and 32) but not as bad as B1 above. The water flow pressure dropped from 35 psi down to 9 psi.

D2 Line (Protected). The damage was reduced drastically. A pinhole size hole occurred at the entrance (Figure 31) with no cracking or flowering of the laminated metal line. The exit (Figure 32) showed a ¼-inch hole in the outside laminate with some outward flowering and possible small cracks in the laminated metal line. The laminate on the inside of the line showed a pinhole size hole. The water flow pressure dropped from 35 psi down to 25 psi.

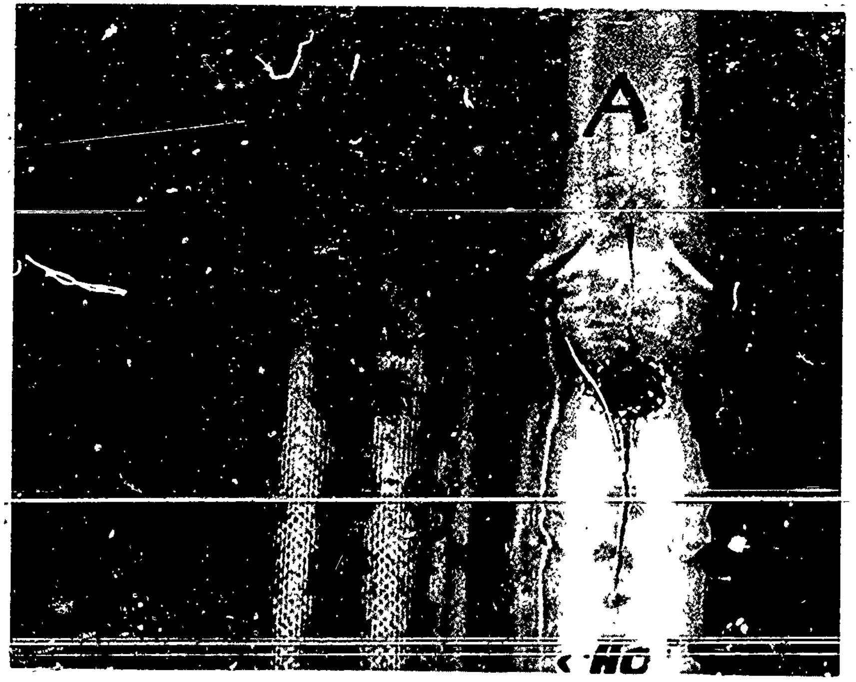


FIGURE 25. A1 UNPROTECTED LINE - A2 PROTECTED LINE - ENTRY SIDE

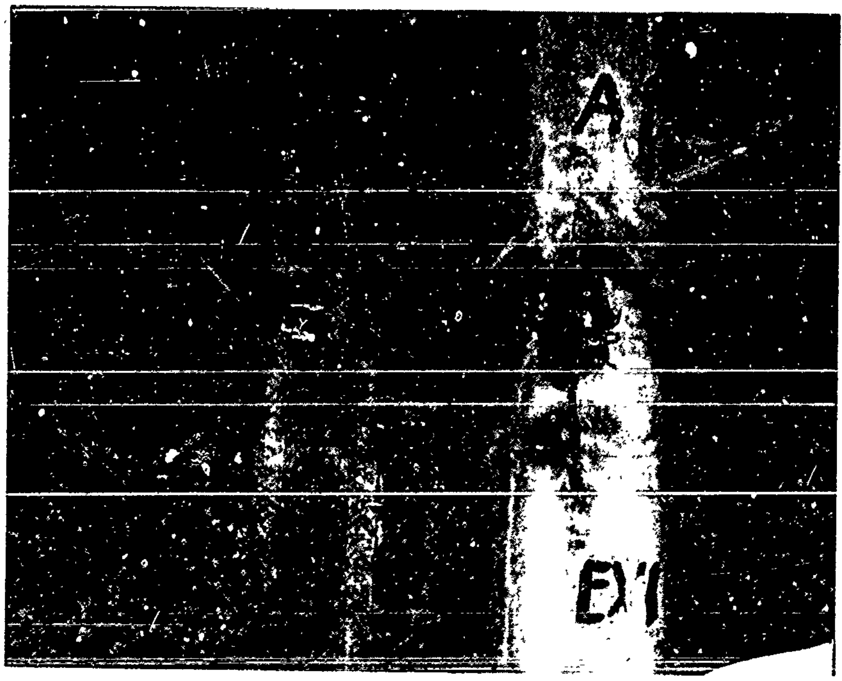


FIGURE 26. A1 UNPROTECTED LINE - A2 PROTECTED LINE - EXIT SIDE

FIGURE 27. B1 UNPROTECTED LINE - B2 PROTECTED LINE - ENTRY SIDE

FIGURE 28. B1 UNPROTECTED LINE - B2 PROTECTED LINE - EXIT SIDE

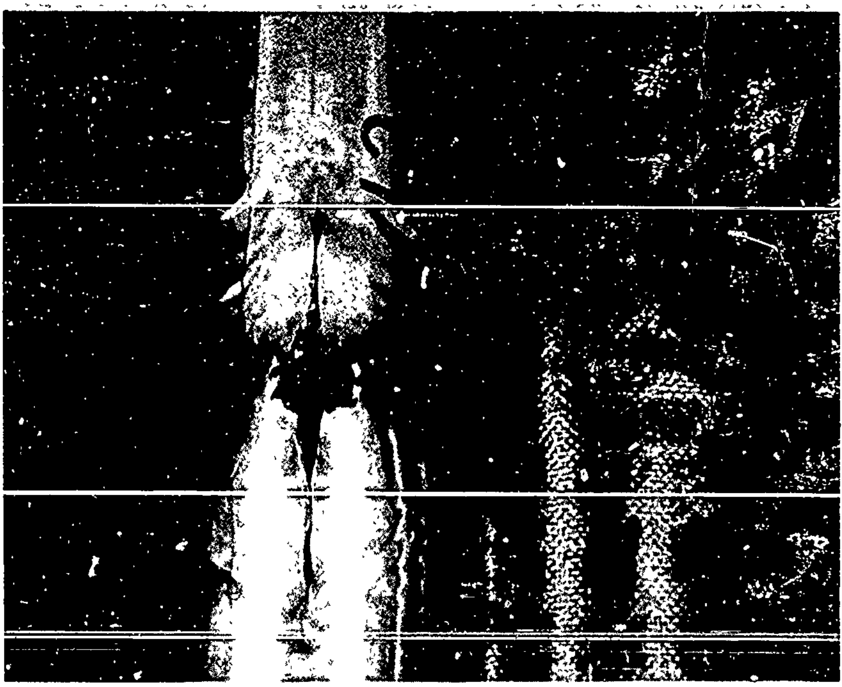


FIGURE 29. C1 UNPROTECTED LINE - C2 PROTECTED LINE - ENTRY SIDE

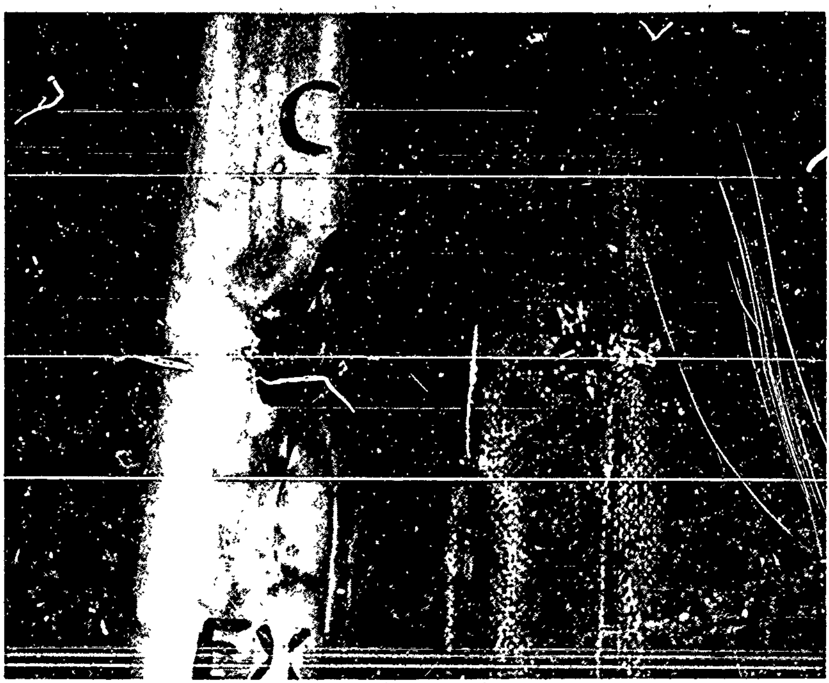


FIGURE 30. C1 UNPROTECTED LINE - C2 PROTECTED LINE - EXIT SIDE

FIGURE 31. D1 UNPROTECTED LINE - D2 PROTECTED LINE - ENTRY SIDE

FIGURE 32. D1 UNPROTECTED LINE - D2 PROTECTED LINE - EXIT SIDE

Test Conclusions

From the results obtained above, it can be concluded that:

1. The aluminum alloy 5052-H38 used in the fabrication of laminated metal lines is less subject to heavy damage than the almost pure 1100-0 type aluminum.

2. With a given type of aluminum (5052-H38 or 1100-0) for the same fuel line wall thickness, the damage is less when more layers of thinner metal are used.

3. The 1-ply flexible ballistic nylon laminate bonded on the inside and outside of the line will drastically reduce the damage to the laminated aluminum lines. Line A2 showed the most promising results.

The results of these tests are summarized in Table II.

Based on the above conclusions, a similar series of tests was conducted with the exception that the projectile used was a .50 caliber AP and the laminated metal fuel lines tested were made of 5052-H38 aluminum foil, .003-inch thick (7 layers) and .004-inch thick (5 layers). The configurations of the lines were similar to the ones shown in Figures 17, 18, 21, and 22, and their fabrications were performed using the above described methods. Also, the ballistic tests were conducted as above; that is, for each test the protected or unprotected laminated metal fuel line was mounted to the fuel line test setup. The water circulating system of the test setup was used in the tests with the water flow pressure set at 35 psi. The gunfiring test was performed using the .50 caliber machine gun. The projectile hit the line in a 90° angle of incidence and 0° yaw. The results obtained in these tests indicated that the degree of damage to the lines did not differ too much from the degree of damage obtained against the .30 caliber AP projectiles. For more details on these results, refer to Table II (Line configurations Q, R, S, and T).

c. Improvement of the Developed Protected Non-Self-Sealing Laminated Aluminum Foil Fuel Lines Concept

In a further optimization of the above developed protected non-self-sealing laminated metal fuel lines, three modified laminated aluminum foil fuel lines were fabricated. The configuration of this modified line is given in Figure 33. The fabrication method used for these lines was similar to the one used for the fabrication of the protected non-self-sealing laminated fuel lines tested above. For the ballistic tests, the lines were mounted to the fuel line test setup shown in Figure 1. Water was used with the flow pressure set at 35 psi. One line was impacted by a .30 caliber AP projectile in a 90° angle of incidence and 0° yaw. The second line was impacted by a slightly tumbled .30 caliber AP projectile, and the third line was impacted by a .50 caliber AP projectile in a 90° angle of incidence and 0° yaw. The results of these tests are given in Table II under the line configuration U.

TABLE II
IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED SEMI-METALLIC FUEL LINES

	PROTECTIVE SYS. USED		WEIGHT ADDED			BALLISTIC TESTS					
LINE CONF	DAMAGE CONTROL NON-SELF-SEALING	SELF-SEALING	TO BARE LINE PER FT² IN LBS.	TO BARE LINE PER LINEAR FT. ID=2" IN LBS	THICKNESS ADDED IN INCHES	PROJECTILE USED: CAL.AP	CONDITIONS OF PROJECTILE IMPACT	INITIAL WATER OR FUEL PRESS. IN LINE (PSI)	FUEL OR WATER PRESS. RECORDED AFTER IMPACT (PSI)	SEALING ACTION	REMARKS
I	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line.	35	12	--	At entry, a ½"-wide dia. hole occurred with outward & inward flowering. A 4" long longitudinal crack across the impact hole occurred (Fig. 25). At the exit, a 5/8" dia. hole was made by the existing projectile. Only outward flowering occurred & a 3" long longitudinal crack across the hole was made (Fig. 26). The weight of this laminated line per ft² is approx. .35 lb. The weight of a standard metal line (0,029" thick) is approx. .39 lb/ft².
J	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	32	--	At entry & exit, pinhold size holes were noted. No apparent cracking or flowering occurred. The flexible laminate on the inside & outside did not show any damage (Figs. 25 & 26).
K	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line.	35	0	--	Catastrophic rupturing occurred at entry & exit & particularly at exit. The line was almost cut in two (Figs. 27 & 28).
L	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	30	--	The 1-ply laminate on the inside & outside of the line kept the damage to pinhole-size holes at entry & exit. Possible small cracking occurred in the laminated line underneath the laminate. No flowering of the metal line was noted (Figs. 27 & 28).

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED SEMI-METALLIC FUEL LINES (Continued)

M	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line.	35	10	--	The pattern of damage occurring with this line was very similar to the one with line I above. However, the damage here was slightly more extensive. (Figs. 29 & 30)
N	Yes	None	.34	.21	1/16	.30	90° angle of incidence, 0° yaw, middle of line.	35	22	--	At the entry side, a pinhole size was made with no cracking of the laminated metal & no flowering. At the exit, the flexible laminate on the inside of the line showed a small hole & no inward flowering of the laminated metal line. The flexible laminate on the outside of the line showed a ¼" hole & outward flowering of the metal line. No cracking of the laminated line occurred. (Figs. 29 & 30)
O	None	None	None	None	0	.30	90° angle of incidence, 0° yaw, middle of line.	35	9	--	Compared to the line K above, the damage here was still severe but to a much lesser degree. (Figs. 31 & 32)
P	Yes	None	.34	.21	1/16	.30	90° angle of incidecne, 0° yaw, middle of line.	35	25	--	A pinhole size hole was made at the entrance with no cracking or flowering of the laminated metal line. The exit showed a ¼" hole in the outside laminate with some outward flowering & small cracks in the laminated metal line. The laminate on the inside of the line showed a pinhole size hole. (Figs. 31 & 32)
Q Similar to Line I above	None	None	None	None	0	.50	90° angle of incidence, 0° yaw, middle of line.	35	10	--	An entry, a 5/8" dia. hole occurred with outward and inward flowering. A 4½" long longitudinal crack across the impact hole was made. At the exit, a 3/4" dia. hole was made Only outward flowering occurred & a 4" long longitudinal crack across the hole was made.

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED SEMI-METALLIC FUEL LINES (Continued)

R Similar to Line J above	Yes	None	.34	.21	1/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	30	--	At entry & exit, pinhole size holes were noted. No apparent cracking or flowering of the metal line occurred. The flexible laminate on the inside & outside did not show any tearing.
S Similar to Line M above	None	None	None	None	0	.50	90° angle of incidence, 0° yaw, middle of line.	35	8	--	The pattern of damage occurring with this line was very similar to the one with Line Q above. However, the damage here was slightly more extensive.
T Similar to Line N above	Yes	None	.34	.21	1/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	28	--	At entry side, a pinhole size hole was made with no cracking of laminated metal & no flowering. At exit, the flexible laminate on inside of the line showed a small hole & no inward flowering. The flexible laminate on the outside of the line showed a 1/8" hole. No cracking of laminated line occurred.
U	Yes	None	.51	.30	3/32	.30	90° angle of incidence, 0° yaw, middle of line.	35	33	--	Entry & exit pinhole size holes were noted. No apparent cracking or flowering of the laminated metal line occurred. The flexible laminate on the inside & outside & sandwiched between the two layers of 5052-H38 Al foil did not show any tearing. As noted, more weight is added for protective system used due to extra layer of laminate used between the metal foil layers. However, this added weight is compensated by using less metal Al foil layers.
U	Yes	None	.51	.30	3/32	.30	Penetrating the line in a slightly tumbled condition & in the middle of the line.	35	27	--	At entry, the projectile left a 3/4" tight slit in laminate & no tearing. At exit, a 5/8" tight slit was noted in the laminate & no tearing. The leakage was small.

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED SEMI-METALLIC FUEL LINES (Continued)

U	Yes	None	.51	.30	3/32	.50	Penetrating at normal incidence in middle of line. (90° angle of incidence, 0° yaw.)	35	30	- -	Pinhole size holes were obtained at entry & exit side of line. The flexible laminate layers kept metal laminated layers from flowering & cracking.
RU	None	None	None	None	0	.50	90° angle of incidence, 0° yaw, middle of line.	35	0	- -	Catastrophic rupturing occurred at entry and exit (see Fig. 34). The weight of this laminated line is approx. .18 lb/ft^2. The Thickness is approx. .017".
SU	Yes	None	.34	.21	1/16	.50	90° angle of incidence, 0° yaw, middle of line.	35	18	- -	At entry, a 1/8" hole was made in the laminate. The laminated metal underneath flowered inward. At the exit, the laminate suffered a 1"long slit with some rupturing of the laminated metal. Fig. 34 (Line B) shows the damage.
TU	Yes	None	.68	.42	1/8	.50	90° angle of incidence, 0° yaw, middle of line.	35	28	- -	At the entry a pinhole size hole was noted in the outside & inner flexible laminate. No flowering of laminated metal line occurred (Fig. 34, Line C). At the exit, a pinhole size hole was noted in the inner flexible laminate & a ½" slit in the outside laminate. No flowering of laminated metal line occurred. (Fig. 34, Line C).
V-1	Yes	Yes	.83	.52	3/8	.50	90° angle of incidence, 0° yaw, middle of line.	35	35	Immediate	At entry and exit sides, pinhole size holes were made which were sealed by the precompressed and fuel sensitive foam. The fuel used was JP-4.

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED SEMI-METALLIC FUEL LINES (Continued)

V-2	Yes	Yes	.94	.57	5/16	.30	Penetrating line at normal incidence & in middle of line.	35	35	Immediate	At entry & exit sides, pinhole size holes were made which were sealed by precompressed & fuel sensitive foam. The fuel used was JP-4.
V-2	Yes	Yes	.94	.57	5/16	30	Penetrating line in a slightly tumbled condition in middle of line. 90° angle of incidence.	35	35	After 1 to 2 min., complete-sealing was achieved.	At entry & exit sides, 3/4" tight long slits were obtained in laminate. No tearing occurred. Immediately after line pressure dropped to 33 psi & a small fuel leak was noted. However, after 1 to 2 min., the leakage stopped & flow pressure returned to initial pressure of 35 psi.
V-2	Yes	yes	.94	.57	5/16	.50	Penetrating at normal incidence in middle of line.	35	33	Did not seal completely at exit side.	A pinhole size hole was made at entry side which sealed immediately. However, exit side showed a 1/8" hole in laminate & a small fuel loss which was reduced after 1-2 min. This leakage persisted & the test was stopped.
W	Yes	Yes	1.11	.66	3/8	.50	Penetrating at normal incidence in middle of line.	35	35	After 1 to 2 min. complete seal was obtained.	Small size holes were made at entry & exit. Immediately after impact, a very small fuel leak occurred at entry & exit. However, after 1-2 min., this leakage stopped & fuel flow pressure reached 35 psi again. When repeating this test, a complete seal was not obtained.
X	Yes	Yes	1.21	.73	13/32	.50	Penetrating at normal incidence in middle of line.	35	35	After 1 to 2 min. complete seal was obtained.	Very small holes were obtained at entry & exit sides of line. Initially, a small fuel leakage occurred at exit side & flow pressure dropped to 33 psi. However, approx. 1½ min. later the leakage stopped & fuel flow pressure returned to 35 psi.

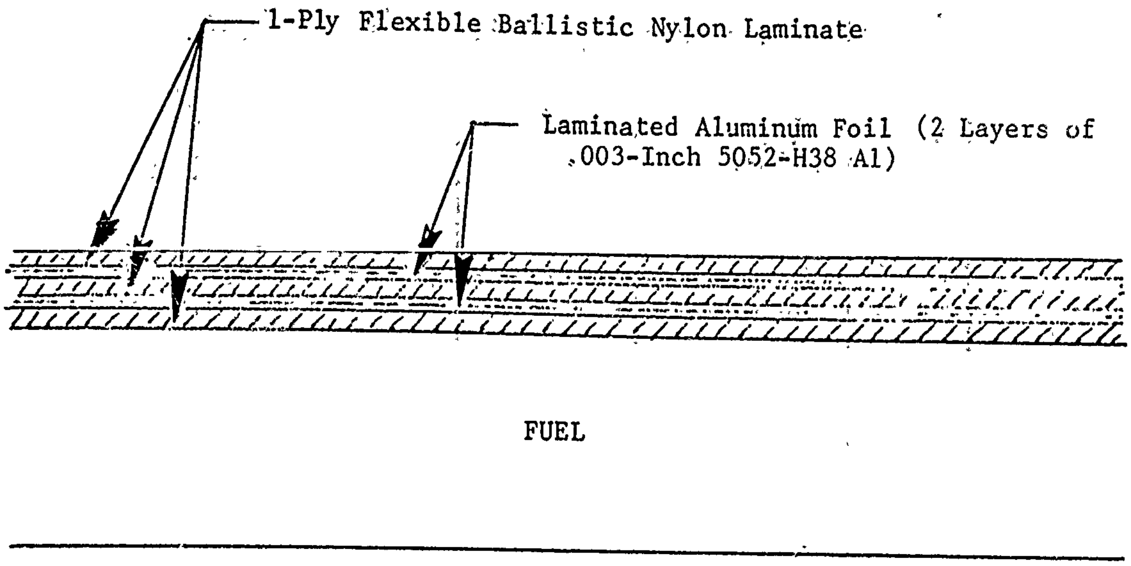


FIGURE 33. NON-FLOWERING SEMI-METALLIC FUEL LINE CONCEPT - LINE CONFIGURATION U

d. Structural Strength Increase of the Laminated Fuel Lines Unprotected and Protected (Non-Self-Sealing)

The laminated aluminum foil fuel lines fabricated and tested up to now used polysulfide 898 sealant as the bonding agent for the aluminum foil layers. This gives a certain softness to the unprotected line due to the flexibility of the cured 898 sealant. By adapting the damage control system to the line this softness is reduced, and it is even further reduced when the damage control and the self-sealing systems are mounted on the line. This softness of the line can be reduced and controlled to the degree desired by selecting a suitable bonding agent. The following bonding agents were selected and investigated: (a) FM-123-2 (modified epoxy) in a thin film (.004-inch thick); (b) 2216 two-part mix epoxy liquid system; and (c) FM-1000 (nylon adhesive) in thin film (.002-inch or .003-inch thick). The FM-123-2 thin film was retained as the most desirable bonding agent. Using the FM-123-2 as the bonding agent, three laminated aluminum foil fuel lines were prepared, one unprotected and two protected with a damage control system.

(1) Fabrication of the Unprotected Reinforced Laminated Aluminum Fuel Lines and Ballistic Test

The configuration of the line was similar to the configuration of the line shown in Figure 18, with the only exception that the reinforced line had three layers of .003-inch thick 5052-H38 aluminum foil bonded with FM-123 film. Its fabrication was performed as follows:

a. A 25-inch by 24-inch piece of 5052-H38 aluminum foil was cut. This size is necessary for a 3-layer laminated line.

b. A 25-inch by 16-inch FM-123-2 piece of film adhesive was cut, laid, and bonded on top of the above cut aluminum foil sheet, leaving an 8-inch bare section at one end of the foil sheet. Then, the film separator on top of the FM-123 adhesive was removed.

c. A metal mold, 30 inches long with 3/8-inch thick walls and a 2.5-inch O.D., was wrapped in non-porous Armalon. This mold with the Armalon was placed at the edge and on top of the bare side of the aluminum foil sheet. Then the mold was rolled over the aluminum foil sheet covered by the epoxy film to produce the 3-layer laminated aluminum foil fuel line.

d. For the curing operation, a PVA film tape was wrapped around the 3 layers of aluminum foil to apply pressure and thus obtain good contact between the aluminum foil layers and the adhesive film. This assembly was then put in an oven at 250F for 1 hour. After cure, the laminated fuel line was removed from the mold. The resulting new fuel line showed a definite increase in structural strength.

Ballistic Test

For this test, the fuel line test setup was used. The new laminated fuel line was mounted to it. The water circulating system was used and the water flow pressure set at 35 psi. A .50 caliber AP projectile was fired in a 90° angle of incidence and 0° yaw. As can be seen in Figure 34 (Line A), the damage was extensive. For more details on the test results, weight and thickness of the line, and other data, refer to Table II.

(2) Fabrication of the Protected Reinforced Laminated Aluminum Fuel Lines and Ballistic Tests

The configurations of the protected lines were similar to the configuration given in Figure 17, with the exception that the reinforced protected lines had three layers of .003-inch thick 5052-H38 Al foil bonded with FM-123 adhesive film. Also, in one of the two protected lines prepared, a 2-ply flexible ballistic nylon laminate was bonded on the outside of the line only. In the second line, a 2-ply flexible laminate was bonded on both the outside and inside of the line. The fabrication procedure used for the first protected line was similar to the procedure used for the unprotected reinforced laminated fuel line above. After completion of the unprotected line section, a 2-ply flexible laminate was wrapped around the line and bonded to the line. The laminate was put on wet and then cured at 180F for 1½ hours.

The fabrication procedure used for the second protected line was as follows:

a. The inner, 2-ply flexible laminate was prepared first using the mold used in the fabrication of the unprotected reinforced line above. The fabrication method used for the flexible laminate has been previously described earlier in the report.

b. A 26-inch by 25-inch Al foil (5052-H38, .003-inch thick) sheet was cut on top of which FM-123 adhesive film was laid covering the whole surface of the foil. The film separator of the adhesive was removed and the foil sheet with adhesive wrapped around the cured laminate covering the mold to give the three layers laminated aluminum foil.

c. For the curing operation, a PVA film tape was wrapped around the three layers of aluminum foil to apply pressure and thus obtain good contact between the aluminum foil layers, the flexible laminate, and the adhesive film. This assembly was then put in an oven at 250F for 1 hour.

d. After cure, an 18-inch by 25-inch ballistic nylon cloth piece was cut and impregnated with 898 polysulfide sealant. The wet cloth was wrapped around the fuel line on the mold. The wet cloth was covered by porous Armalon around which PVA film tape was wound to apply pressure and obtain a good bond between the nylon cloth and the laminated metal foil line.

e. The assembly was then put in an oven at 200F for 1½ hours. After cure, the protected reinforced laminated foil line was removed from the mold.

Ballistic Tests

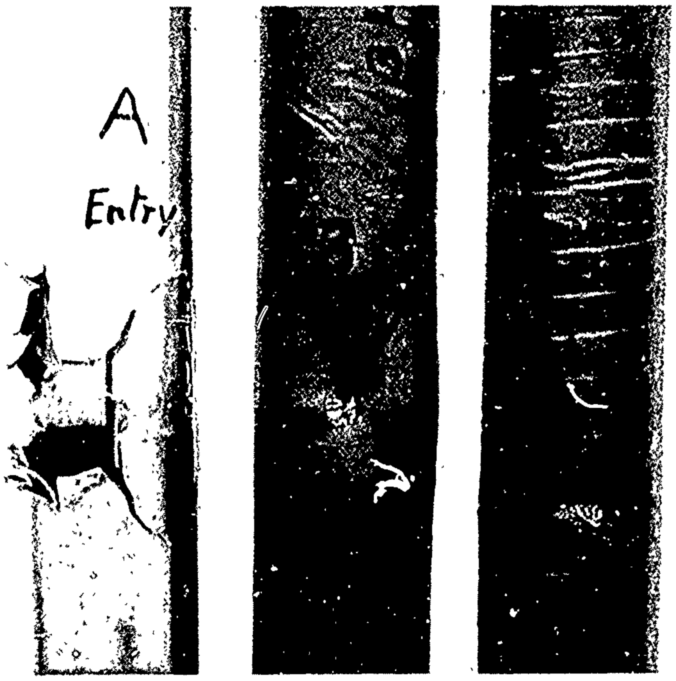
In these tests, each line was mounted to the test setup and the water flow pressure was set at 35 psi. Into both lines, a .50 caliber AP projectile was fired in a 90° angle of incidence and 0° yaw. Figure 34 shows the results. The fuel line marked by a B is the laminated line containing the 2-ply flexible laminate on the outside of the fuel line, and the fuel line marked by a C is the laminated fuel line containing the 2-ply flexible laminate on the outside and inside of the line. More details of the results are given in Table II.

Test Conclusions

- The FM-123-2 adhesive film used for bonding the aluminum foil layers definitely increased the structural strength of the laminated lines.
- Because of the structural strength increase, fewer layers of aluminum foil can be used and thus lower the weight of the laminated lines and still give the same promising results as the laminated lines using a greater amount of aluminum foil layers and 898 sealant as the bonding agent.

2. Preparation of Laminated Self-Sealing Aluminum Foil Fuel Lines and Ballistic Tests

Six laminated self-sealing aluminum foil fuel lines were fabricated. Of the six, one has the configuration shown in Figure 35, three have the configuration shown in Figure 36, the fifth has the configuration shown in Figure 37, and the sixth has the configuration shown in Figure 38. The procedure used for the fabrication of these lines was similar to the one described under Section B1a(2) which was the procedure used for the fabrication of protected non-self-sealing laminated lines. The only exception here was that an additional step was taken to sandwich foam layers either between flexible ballistic nylon laminates or laminated aluminum foil layers. The foam was put under a precompressed state by means of a PVA film tape which was applied in such a way that it exerted a controlled pressure while the foam was being bonded either to the flexible laminates or the laminated aluminum foil. Figures 39, 40, 41, and 42 show cross-sections of each line configuration depicting the foam layer or layers sandwiched between either the flexible laminates or the laminated aluminum foil. The figures illustrate the line configurations V-1, V-2, W, and X, respectively, in Table II.



View of Entry Sides

View of Exit Sides

FIGURE 34. LAMINATED Al FOIL FUEL LINES (3 LAYERS OF .003-INCH 5052-H38 Al, FM-123 ADHESIVE) PROTECTED AND UNPROTECTED

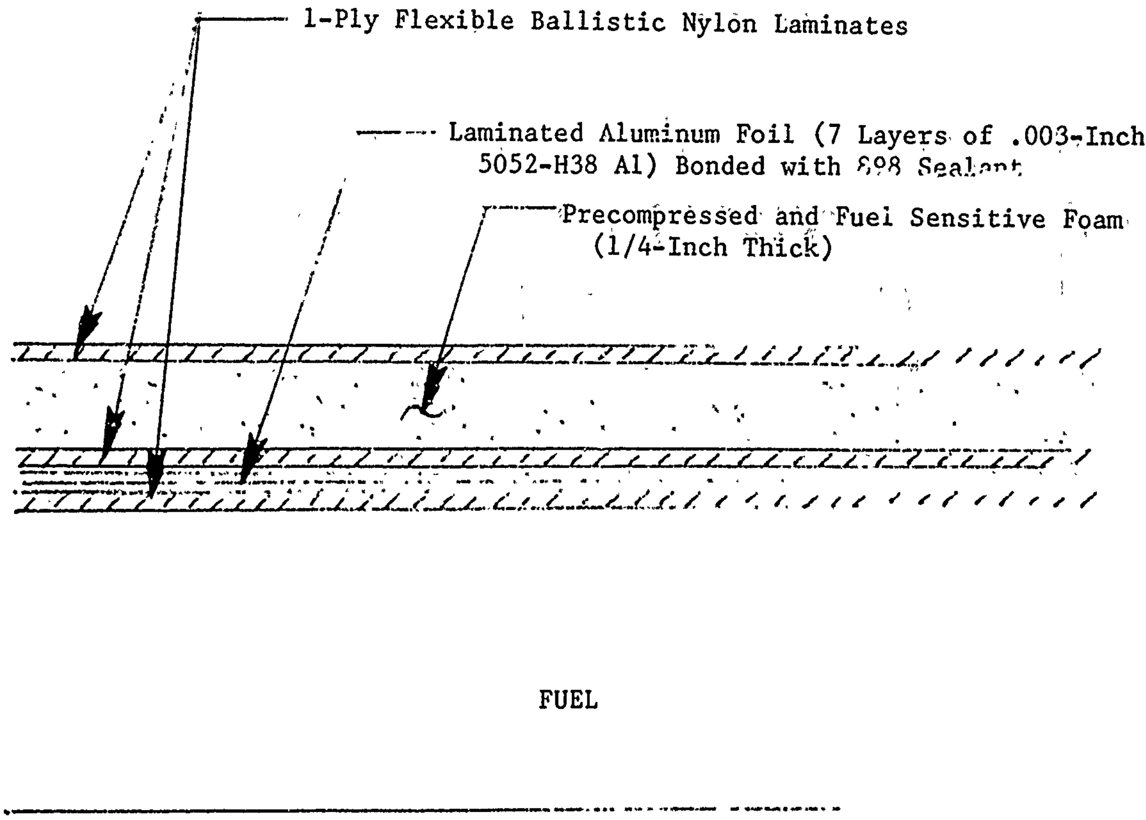


FIGURE 35. NON-FLOWERING SEMI-METALLIC FUEL LINE SELF-SEALING CONCEPT - LINE CONFIGURATION V-1

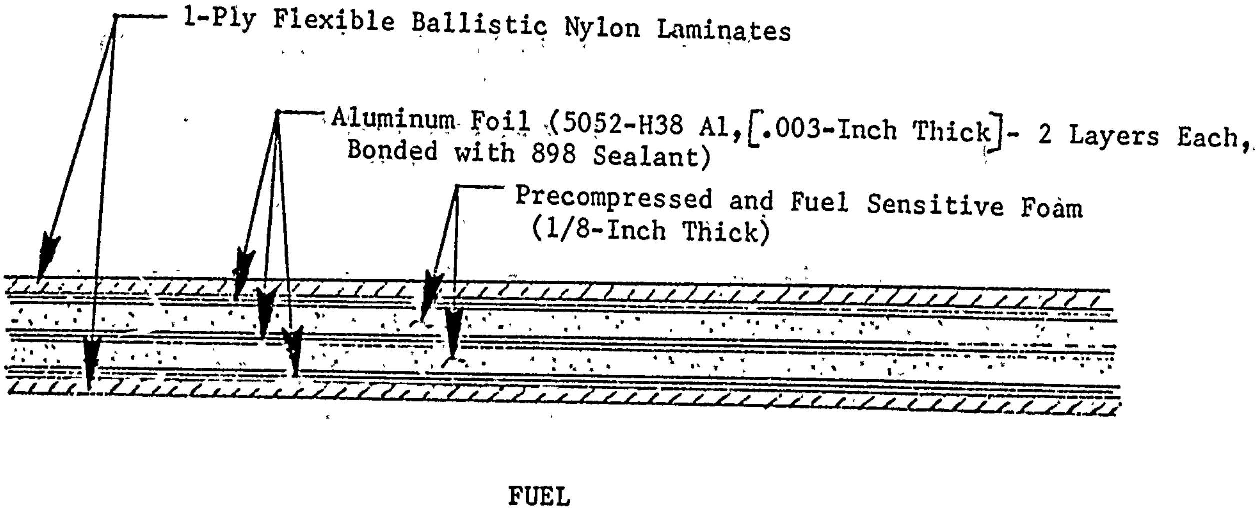


FIGURE 36. NON-FLOWERING SEMI-METALLIC FUEL LINE SELF-SEALING CONCEPT - LINE CONFIGURATION V-2

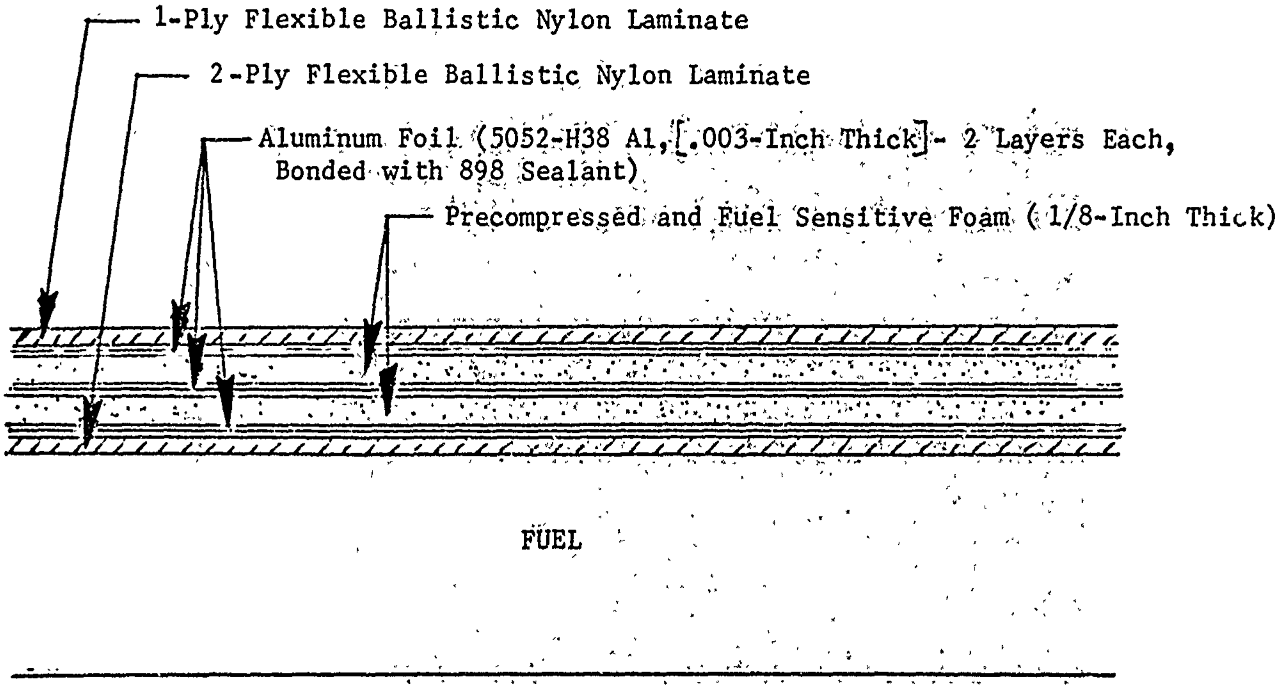


FIGURE 37. NON-FLOWERING SEMI-METALLIC FUEL LINE SELF-SEALING CONCEPT - LINE CONFIGURATION W

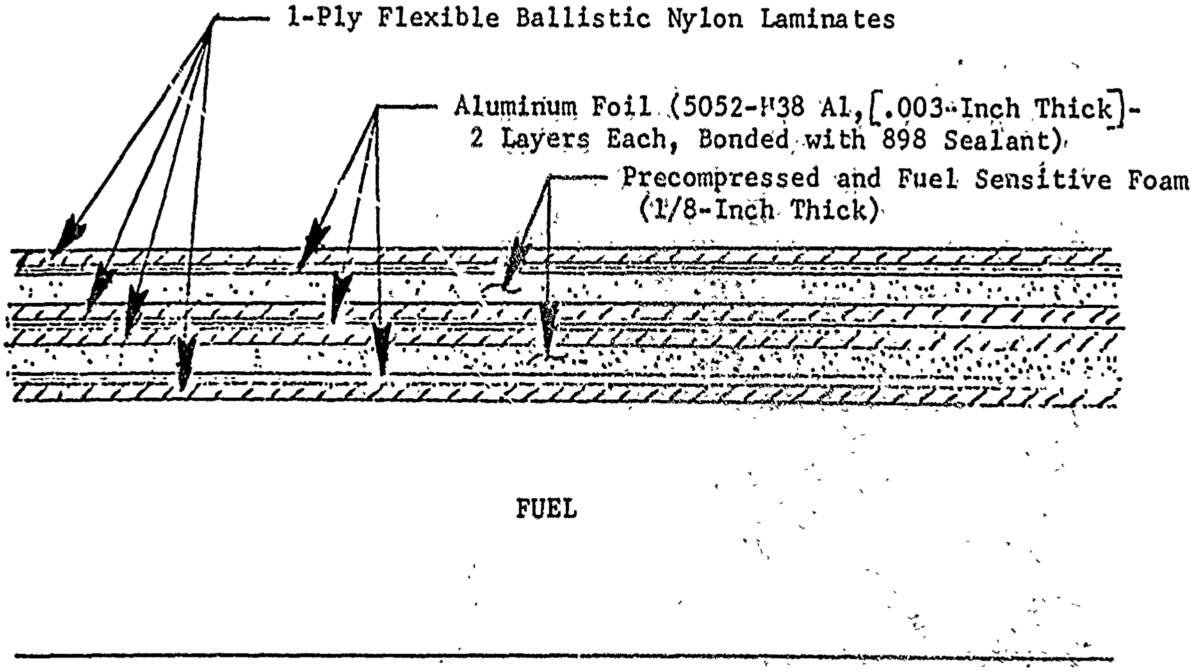


FIGURE 38. NON-FLOWERING SEMI-METALLIC SELF-SEALING CONCEPT - LINE CONFIGURATION X

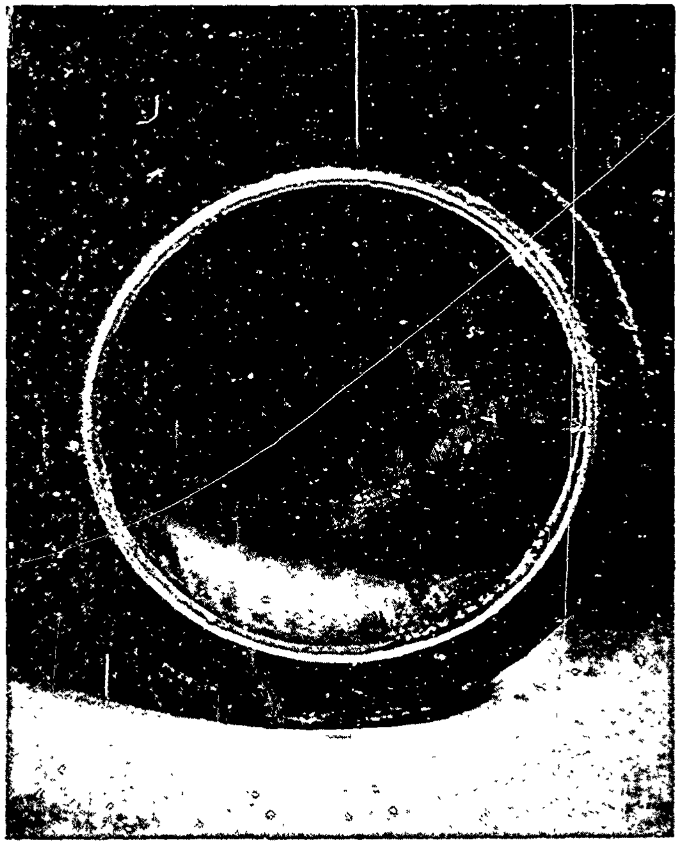


FIGURE 39. LINE CONFIGURATION V-1

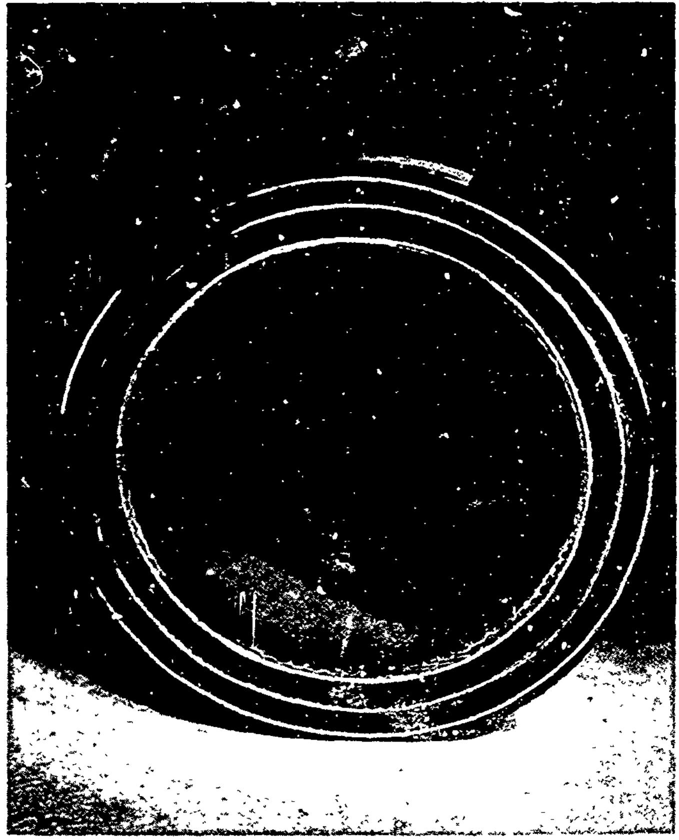


FIGURE 40. LINE CONFIGURATION V-2

FIGURE 41. LINE CONFIGURATION W

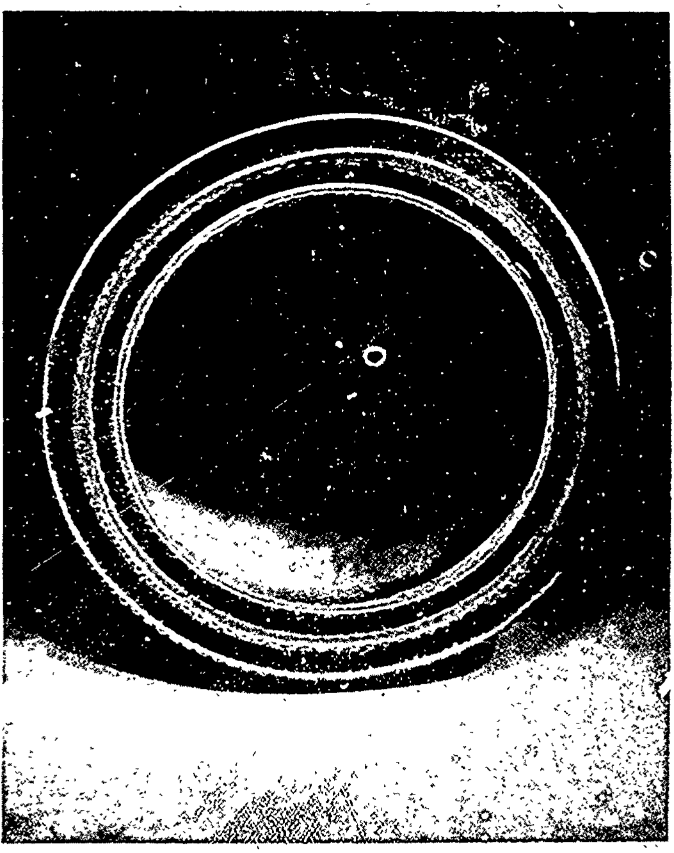


FIGURE 42. LINE CONFIGURATION X

Ballistic Tests

In the ballistic tests, each line was mounted to the test setup and the fuel recycling system was used (see Figure 1). The fuel flow pressure was set at 35 psi. In the actual tests, the line with the configuration V-1 was impacted by a .30 caliber AP projectile in a 90° angle of incidence and 0° yaw. The three lines with the configuration V-2 were impacted, one by a .30 caliber AP projectile in a 90° angle of incidence and 0° yaw, the second by a .30 caliber AP projectile in a 90° angle of incidence and slight tumbling, and the third by a .50 caliber AP projectile in a 90° angle of incidence and 0° yaw. The results of all these self-sealing tests are given in Table II.

C. DEVELOPMENT OF NON-FLOWERING PLASTIC FUEL LINES

If the materials, design, and fabrication techniques are properly selected in the fabrication of plastic fuel lines, the resulting lines should not flower or rupture and should reduce the impact damage to a sealable hole or even seal the hole if a self-sealing system is imbedded in the fuel line. Rigid, semi-rigid, and flexible plastic fuel lines can be prepared. The rigidity or flexibility of the lines will depend upon the plastic components used. It is believed that flexibility in the fuel line will enhance the protection efficiency of the fuel line. A very rigid plastic fuel line will tend to rupture or crack easily; a more flexible plastic fuel line will not rupture and will reduce the damage to a small sealable hole. Reinforcements such as high-strength cloth, high-strength filaments, or high-strength metal wire, imbedded in the resin, will vary and control the strength of the fuel line tubing. Keeping in mind the above considerations, a series of plastic fuel lines were initially prepared and ballistically tested against .30 caliber AP projectiles.

1. Preparation of Plastic Fuel Lines

a. Plastic Fuel Lines Fabrication Procedure

A procedure has been developed for making plastic fuel lines 2½ inches in diameter and 3½ feet long. The line configuration is shown in Figure 43. An aluminum tube is used as the mold. Non-porous Armalon is wrapped around the tube as a mold release agent. Ballistic nylon layers are wrapped over the Armalon. The ballistic nylon is impregnated with a mixture of Epon 828, butyl glycidyl ether and Versamid 125. The wet ballistic nylon is held in place by wrapping with polyvinyl alcohol plastic tape. The layup is cured in an oven at 100F for 4 hours. After cure the metal tube is separated from the plastic tube.

b. Fabrication of Unprotected Plastic Fuel Lines and Ballistic Tests

Using the technique described above for preparing plastic fuel lines a 2½-inch diameter and 3½-foot long plastic fuel line was prepared. It was made up of three approximately 12-inch test sections containing 2-ply, 3-ply, and 4-ply ballistic nylon laminate sections. The ballistic nylon was

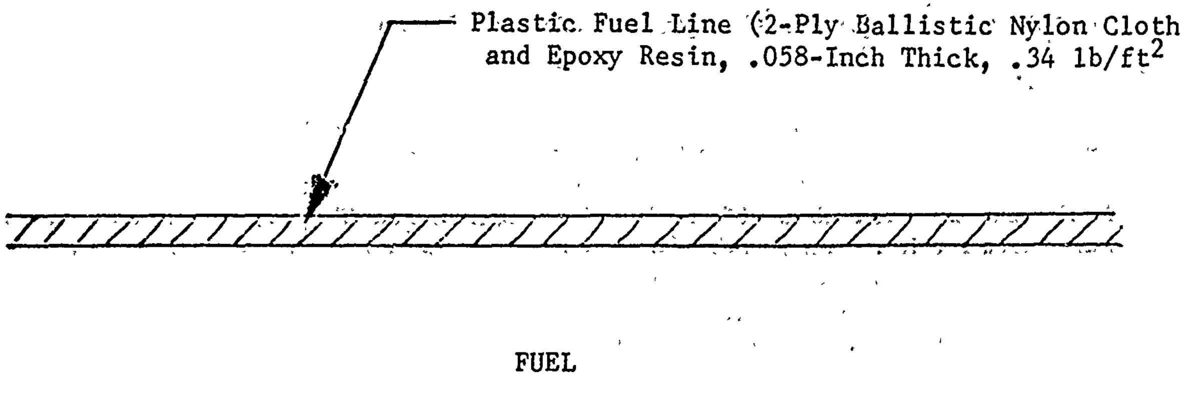


FIGURE 43. NON-FLOWERING PLASTIC FUEL LINE - LINE CONFIGURATION Y

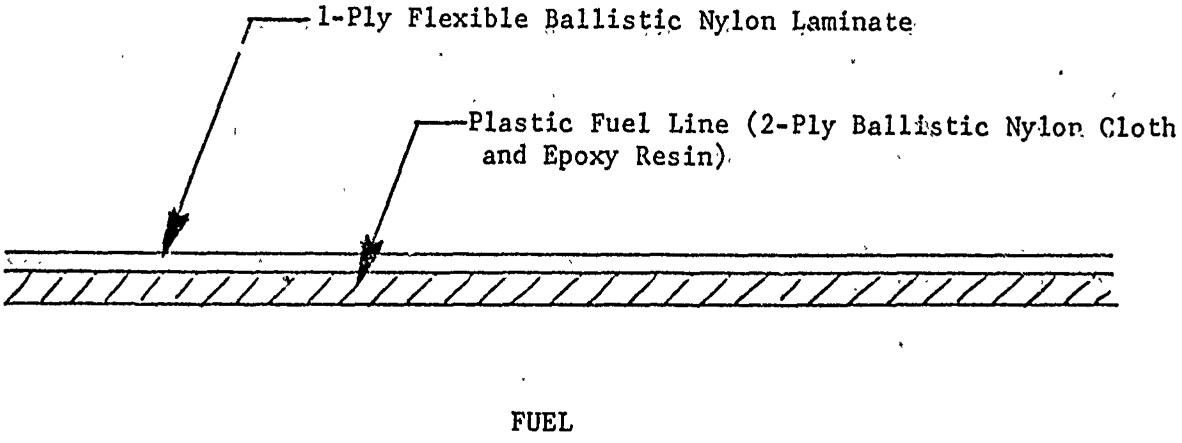


FIGURE 44. NON-FLOWERING PROTECTED PLASTIC FUEL LINE - LINE CONFIGURATION Z

impregnated with a mixture of Epon 828 and Versamid 125 (in a 2:1 ratio). Butyl glycidyl ether was added to the mixture for thinning of the mixture and to allow better penetration of the mixture into the ballistic nylon cloth.

The gunfiring was performed using the .30 caliber rifle with a 1-turn-per-10-inches rifling. The plastic fuel line was mounted to the fuel line test setup. The water circulating system was used and the water flow pressure was set at 35 psi. The first shot (.30 caliber AP) was fired into the 2-ply fuel line section at a 90° angle of incidence and 0° yaw. At the entrance, only a small hole occurred. At the exit, a ½-inch slit with some minor fringing of nylon occurred. The water flow pressure through the line had dropped down to approximately 22 psi. Table III contains the results of this test (see line configuration Y-1).

The shot in the 3-ply fuel line section gave a small hole at the entrance and a 1-inch slit with some minor fringing of nylon occurring at the exit. The water flow pressure dropped from 35 psi down to 27 psi.

The shot into the 4-ply fuel line section showed a tiny hole at the entrance side of the line and a ½-inch slit with minor fringing of the nylon at the exit side of the line. The water flow pressure dropped from 35 psi down to 30 psi.

After each of the above shots, the damage was repaired using wet epoxy nylon laminate (2-ply) patches wrapped around the damaged area. The patches were cured in an oven at 180F for 1½ hours. After repair, similar shots to those above were repeated. The results obtained were almost identical. A nonmetallic fuel line using PRD-49 high-strength fabric (2-ply) impregnated with 828 epoxy resin was compared ballistically with a nonmetallic fuel line using ballistic nylon cloth (2-ply) impregnated with 828 epoxy resin. The results indicated that the line using the ballistic nylon cloth was superior in limiting damage to the fuel line

In another series of tests, a number of plastic fuel lines were prepared where the effect of the flexibility of the plastic fuel lines was investigated. These plastic fuel lines were made of epoxy/nylon. The flexibility of these lines was varied by using different epoxy resin (828 type) mixture formulations In the previous fabrication of epoxy fuel lines, the ratio of 828 resin to 125 Versamid was 2:1. Using this ratio, the resulting plastic line tends to become slightly brittle. This probably accounts for the fringing of the ballistic nylon cloth when the fuel line is ballistically tested. To lower the brittleness of the plastic fuel line material, the ratio of 828 resin to 125 Versamid was varied (2:1.5 in one case and 1:1 in another case). Using these two new ratios, several plastic fuel lines were prepared having an I.D. of 2½ inches and a length of 3½ feet. The number of ballistic nylon cloth layers used in all the lines was two.

The techniques used for the fabrication of the lines was the one described above. The new lines with the ratios of 2:1.5 and 1.1 showed a definite higher flexibility than those previously prepared using the 2:1 epoxy/Versamid ratio. The degree of flexibility increased as the amount of Versamid was increased.

The above plastic fuel lines were ballistically tested against .30 caliber AP projectiles using the fuel line test setup. For each test, the unprotected plastic fuel line was mounted to the fuel line test setup. The water circulating system was used with the water flow pressure set at 35 psi. The gunfiring test was performed using the .30 caliber rifle with a 1-turn-per-10-inches rifling.

In the test of the fuel line using the 2:1.5 epoxy/Versamid ratio, the projectile hit the line in a 90° angle of incidence and 0° yaw. After impact, the damage which occurred was a small-size hole at the entry with no cracking (low brittleness) of the laminated fuel line wall and low degree of fringing of the ballistic nylon cloth. At the exit, the projectile left a ½-inch long slit with a minor degree of fringing on the inside or outside of the line. Similar shots with similar fuel lines were repeated two times and similar results were obtained. In all cases, the water flow pressure through the line after the shots dropped from 35 psi down to 25 psi. More details of the results are given in Table III (see line configuration Y-2).

The fuel lines using the 1:1 epoxy/Versamid ratio showed similar or slightly better results when compared with the lines using the 2:1.5 epoxy/-Versamid ratio. The results of this test are given in Table III (see line configuration Y-3).

c. Fabrication of Protected Plastic Fuel Lines and Ballistic Tests

A 2½-inch diameter by 3½-foot long 2-ply ballistic nylon plastic fuel line was fabricated using the technique described above for preparing plastic fuel lines. The resin used was a mixture of Epon 828 and Versamid 125 (in a 2:1 ratio). Butyl glycidyl ether was added for thinning of the mixture and to allow better penetration of the mixture into the ballistic nylon cloth. Upon completion of the semi-flexible fuel line, half of the line length was covered with 1 ply of flexible ballistic nylon and the other half with 2 plies of flexible ballistic nylon laminate using polysulfide 898 as the impregnating sealant. The configuration of this line is given in Figure 44.

The gunfiring test was performed using the .30 caliber rifle with a 1-turn-per-10-inches rifling. The 2-ply epoxy plastic fuel line with the protective system (flexible laminate) bonded was mounted to the fuel line test setup. The water circulating system was used in this test with the water flow pressure set at 35 psi.

The first shot (.30 caliber AP) was fired into the section protected by 1 ply of the flexible composite at a 90° angle of incidence and 0° yaw. At the entrance (Figure 45), a pinhole size hole resulted, and on the inside of the line which was not protected, no fringing of nylon was noted. At the exit, the projectile left a ½-inch long slit with some fringing of nylon on the outside (see Figure 46) of the line and no fringing on the inside. The water flow pressure through the line dropped from 35 psi down to 29 psi. This, compared to test results on an unprotected 2-ply ballistic nylon plastic fuel line, is a 7 psi decrease in pressure drop. For more results see Table III (line configuration Z-1).

TABLE III
IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED PLASTIC FUEL LINES

LINE CONF	PROTECTIVE SYS.USED		WEIGHT ADDED		THICKNESS ADDED IN INCHES	BALLISTIC TESTS					REMARKS
	DAMAGE CONTROL NON-SELF-SEALING	SELF-SEALING	TO BARE LINE PER FT^2 IN LBS.	TO BARE LINE PER LINEAR FT. ID=2½"IN LBS		PROJECTILE USED: CAL.AP	CONDITIONS OF PROJECTILE IMPACT	INITIAL WATER OR FUEL PRESS. IN LINE (PSI)	FUEL OR WATER PRESS.RECORDED AFTER IMPACT (PSI)	SEALING ACTION	
Y-1 Ratio of 828 epoxy resin to 125 versamid was 2:1.	None	None	None	None	0	.30	Penetrating at normal incidence in middle of line.	35	22	--	At entrance, only a small hole occurred. At exit, a ½" slit with some minor fringing of nylon occurred. The thickness of line was .058" (2-ply) & weight .34 lb/ft^2 or .21 lb/linear ft. of line. A 3-ply plastic line gave a pressure drop from 35 to 27 psi & a 4-ply plastic line gave a pressure drop from 35 to 30 psi.
Y-2 Ratio of 828 epoxy resin to 125 versamid was 2:1.5.	None	None	None	None	0	.30	Penetrating at normal incidence in middle of line.	35	25	--	Damage obtained here was similar to one obtained with Y-1 line above with the exception that less fringing of nylon was experienced in this test. The higher flexibility of line was responsible for this.
Y-3 Ratio of 828 epoxy resin to 125 versamid was 1:1.	None	None	None	None	0	.30	Penetrating at normal incidence in middle of line.	35	26	--	Pattern of damage was identical to damage of Line Y (ratio 2:1.5) above. Only exception was that flow pressure dropped only to 26 psi.
Z-1 Ratio of 828 epoxy resin to 125 versamid was 2:1.	Yes	None	.17	.10	1/32	.30	Penetration at normal incidence in middle of line.	35	29	--	At entry, a pinhole size hole occurred & on inside no fringing of nylon was noted. At exit, a ½" tight slit was experienced (Figs. 45 & 46). A similar line but with a 2-ply laminate instead of a 1-ply laminate was ballistically tested. Results were similer to 1-ply laminate protection except that flow pressure dropped to 32 psi only.

IMPACT TEST RESULTS ON UNPROTECTED AND PROTECTED PLASTIC FUEL LINES (Continued)

Z-2 Ratio of epoxy resin to 125 versamid was 2:1.5.	Yes	None	.17	.10	1/32	.30	Penetrating at normal incidence in middle of line.	35	32	--	Pinhole size holes were obtained at entry & exit. Leakage was small.
XY Ratio of 828 epoxy resin to 125 versamid was 2:1.5	Yes	None	.34	.21	1/16	.30	Penetrating at normal incidence in middle of line.	35	33	--	Pinhole size holes occurred at entry & exit. Leakage was small.
XZ Ratio of 828 epoxy resin to 125 versamid was 2:1.5.	Yes	Yes	.49	.30	5/16	.30	Penetrating at normal incidence in middle of line.	35	35	Immediate	Pinhole size holes were noted. No leakage & sealing was immediate. A similar line tested against .50 cal. AP projectile gave practically the same results. The only exception was that sealing occurred within 1 to 2 minutes. (See Figs. 50 & 51).

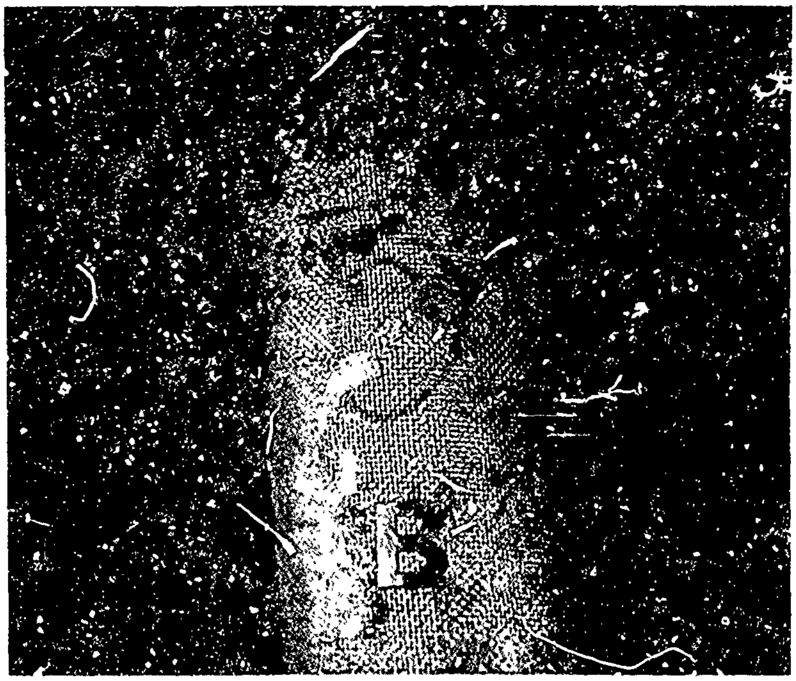


FIGURE 45. PROTECTED PLASTIC FUEL LINE (1-PLY FLEXIBLE LAMINATE) - ENTRY SIDE

FIGURE 46. PROTECTED PLASTIC FUEL LINE (1-PLY FLEXIBLE LAMINATE) - EXIT SIDE

The .30 caliber AP shot into the section protected by the 2-ply outer cover at a 90° angle of incidence and 0° yaw showed, again, a small hole at the entry of the line and no fringing of nylon on the inside of the line. At the exit, a 3/8-inch long slit occurred with no fringing of nylon on the inside or outside of the line. The water flow pressure dropped from 35 psi down to 32 psi. Table III contains more results (see line configuration Z-1).

In another series of tests, two types of protected 2-ply ballistic nylon plastic fuel lines were prepared using the more flexible plastic fuel lines (epoxy/Versamid ratio of 2:1.5). In one case a 1-ply flexible ballistic nylon laminate (using 898 sealant as the impregnating resin) was wrapped around on the outside of the lines and bonded to the lines using 898 sealant material (see Figure 44). In the other case, a 1-ply flexible ballistic nylon laminate (using 898 sealant as the impregnating resin) was wrapped around the outside and the inside of the lines and bonded with 898 sealant (see Figure 47). In the latter case, the fabrication technique was as follows: an aluminum tube (O.D. of 2½ inches) was used as the mold. Non-porous Armalon was wrapped around the tube as the mold releasing agent. A measured 1-ply flexible ballistic nylon laminate was wrapped over the Armalon. The two ends (overlapping by ½-inch) of the 1-ply laminate were bonded together using 898 sealant under pressure at 180°F for 1½ hours. After bonding of the 1-ply laminate the impregnated ballistic nylon layers (two) with the mixture of Epon 828, butyl glycidyl ether, and Versamid 125 (a ratio of 2:1.5) were wrapped over the 1-ply laminate. The wet ballistic nylon cloth was held in place and bonded to the laminate by wrapping with polyvinyl alcohol plastic tape (to apply pressure). The layup was cured in an oven at 180°F for 1½ hours. After cure, a 1-ply flexible ballistic nylon laminate (using 898 sealant as the impregnating resin) was wrapped around the outside of the lines and bonded to the lines using 898 sealant material which was cured at 180°F for 1½ hours.

Ballistic tests were conducted with these protected lines similar to the ones conducted with the unprotected lines. The results obtained showed that the protected lines performed very well and particularly the lines protected on the inside and outside showed very promising results. In all cases, the damage was low and the water flow pressure through the fuel line after the shots dropped only from 35 psi down to 32-33 psi. The detailed results are given in Table III. The line configuration Z-2 is the line with a 1-ply flexible laminate bonded on the outside of the plastic line and configuration XY is the line with a 1-ply flexible laminate bonded on the outside and inside of the plastic line.

A different type of protective system for plastic fuel lines was investigated. In it a layer of foam is utilized as an additional damage control system and/or a self-sealing system (see Figure 48). A 2-ply ballistic nylon plastic tube using this type system was prepared using the technique described above. A ½-inch layer of natural rubber foam sheet was wrapped around the plastic tube and bonded using 898 polysulfide sealant. The foam was put under precompression. A layer of ballistic nylon cloth impregnated with 898 sealant was wrapped over the natural rubber foam layer and kept in place with a wrap of porous Armalon. The layup was cured in an oven at 100°F for 4 hours. Figure 49 shows a cross-section of the line depicting the foam layer sandwiched between the plastic line and the flexible laminate.

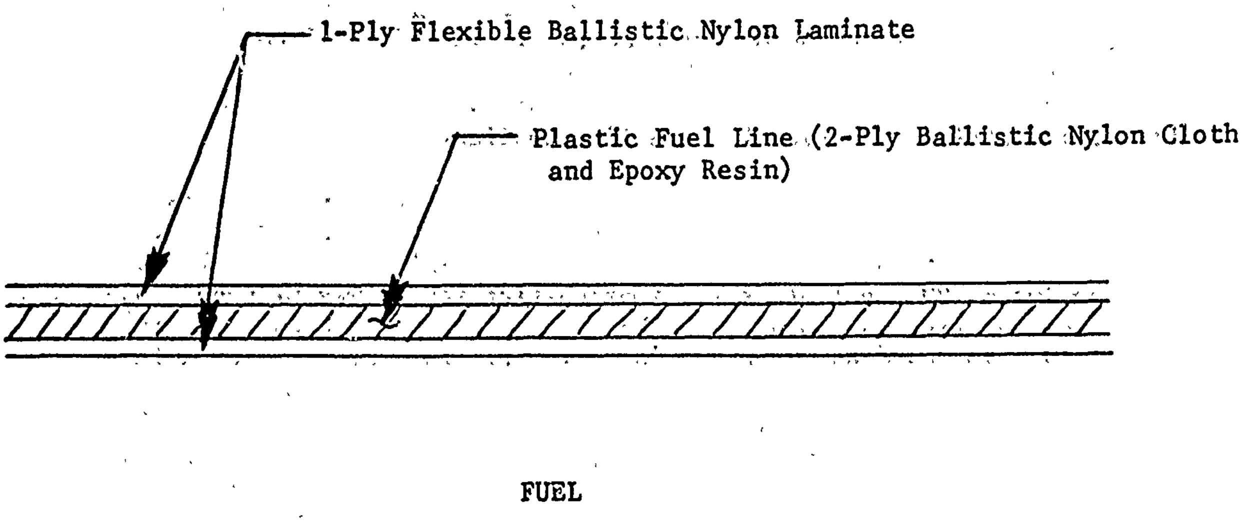


FIGURE 47. NON-FLOWERING PROTECTED PLASTIC FUEL LINE - LINE CONFIGURATION XY

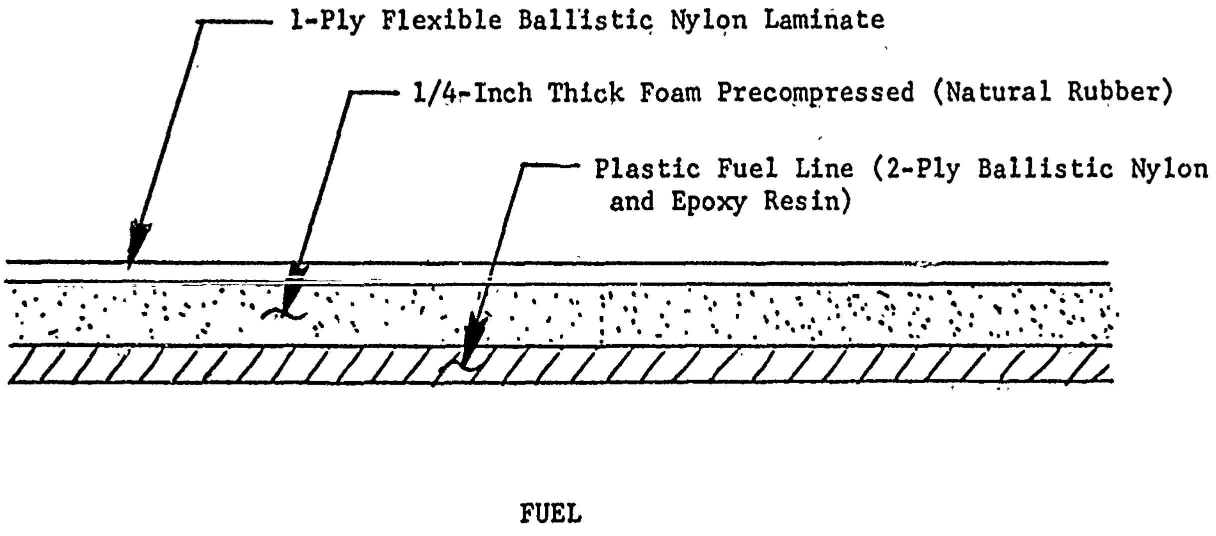


FIGURE 48. NON-FLOWERING SELF-SEALING PLASTIC FUEL LINE - LINE CONFIGURATION XZ

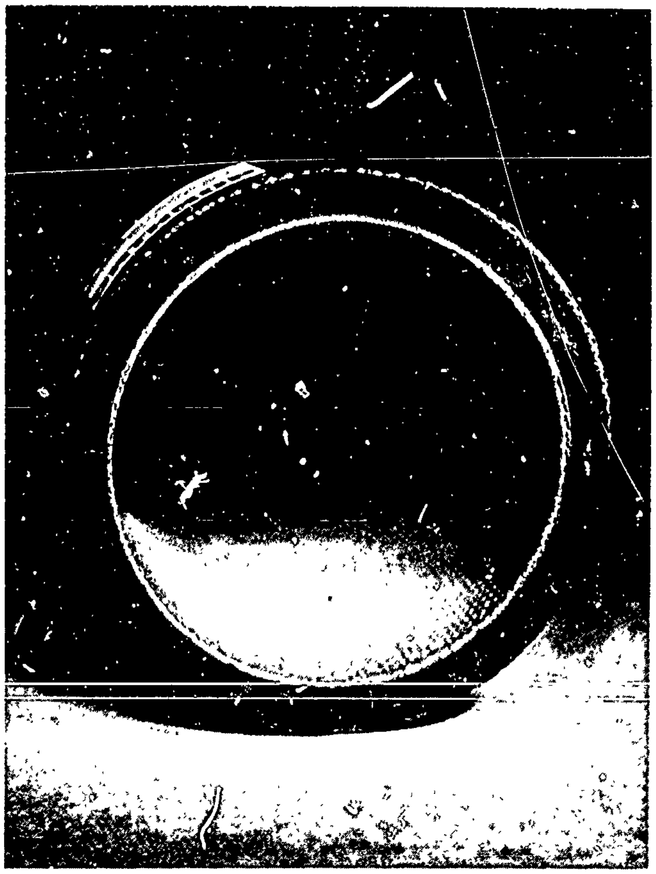


FIGURE 49. LINE CONFIGURATION XZ

The completed line was mounted to the fuel line test setup. The water circulating system was used in this test, with the water flow pressure set at 35 psi. A .30 caliber AP projectile was fired at a 90° angle of incidence and 0° yaw. As shown in Figure 50 and 51, the damage which occurred at both the entrance and exit sides was only a pinhole size hole with no fringing of nylon, Upon impact, the line pressure dropped slightly (as witnessed on a high-speed motion picture) but returned to the initial pressure of 35 psi within a short period of time indicating sealing of the puncture. A similar test was conducted with a similar protected plastic line with the only exception that fuel was used instead of water as the circulating fluid. In this case, the natural rubber foam performed even better inasmuch as sealing was obtained by both the precompression of the foam and the swelling of the foam in contact with the fuel.

D. DETERMINATION OF BURST AND COLLAPSE PRESSURES ON UNPROTECTED AND PROTECTED (NON-SELF-SEALING) LAMINATED AND PLASTIC FUEL LINES

A newly designed or developed fuel line has to be able to withstand the pressure changes which occur during aircraft operation. In view of this, tests were conducted to determine the burst and collapse resistance of unprotected and protected laminated aluminum foil fuel lines (the soft and rigid types) and unprotected and protected plastic fuel lines. The lines which were subjected to these tests are identified below:

a. Unprotected laminated aluminum foil fuel line with line configuration shown in Figure 18.

b. Protected laminated aluminum foil fuel line with line configuration shown in Figure 17.

c. Unprotected reinforced laminated aluminum foil fuel line (Line A; see "Bld(1) Ballistic Tests" section, page 41 and Figure 18).

d. Protected reinforced laminated aluminum foil fuel line (Line B; see "Bld(2) Ballistic Tests" section, page 42 and Figure 17).

e. Protected reinforced laminated aluminum foil fuel line (Line C; see "Bld(2) Ballistic Tests" section, page 42 and Figure 17).

f. Unprotected plastic fuel line with line configuration shown in Figure 43.

g. Protected plastic fuel line with line configuration shown in Figure 44,

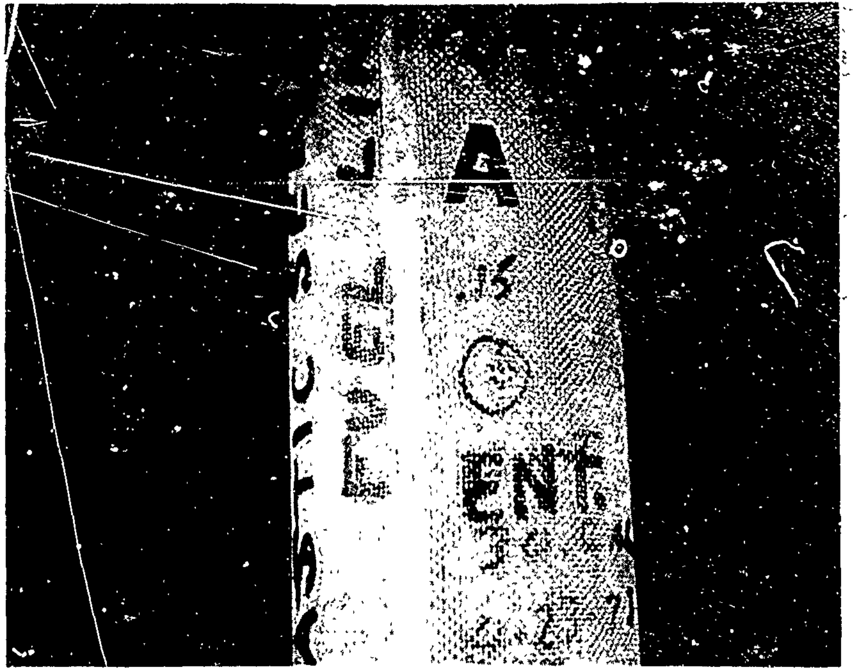


FIGURE 50. PROTECTED PLASTIC FUEL LINE (FLEXIBLE LAMINATE AND FOAM) - ENTRY SIDE

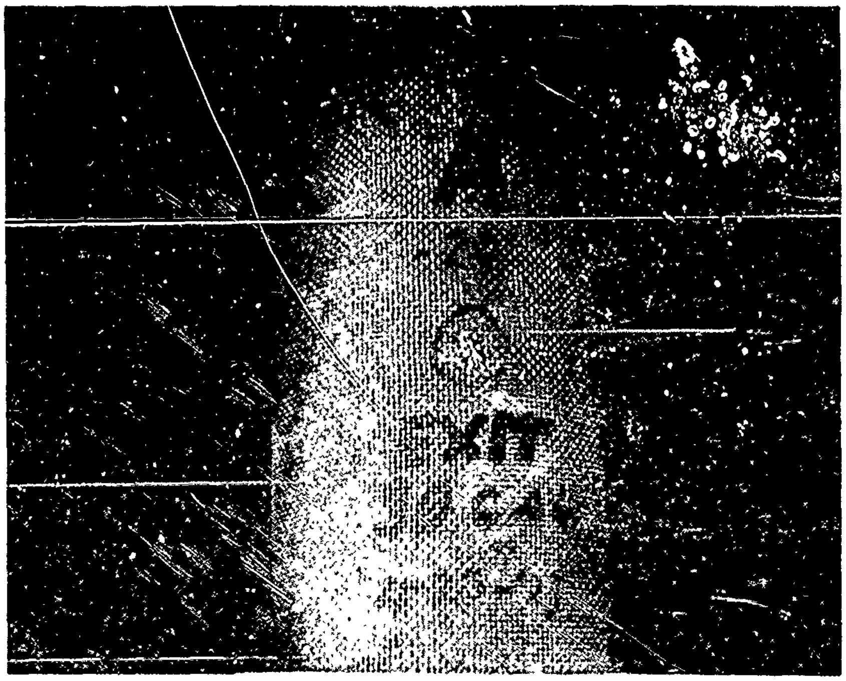


FIGURE 51. PROTECTED PLASTIC FUEL LINE (FLEXIBLE LAMINATE AND FOAM) - EXIT SIDE

1. Burst Pressure Test

a. Burst Pressure Test Setup

This setup is shown in Figure 52. As shown, it consists of a clamping device in which the lines to be tested are clamped and a manifold comprised of a pressure gage, a pressurized air inlet and a water inlet. To apply pressure a hand-operated pump is used.

b. Procedure of Test

- Mount the line to the setup as shown in Figure 52. To obtain a tight seal at both ends of the line, rubber stoppers are used.
- Fill the line with water and gradually apply the water pressure to maximum (55-60 psi). Observe if there is any deformation of the line.
- If no change of the line is observed to that point, then proceed with increasing the pressure gradually by using the hand-operated pump of the setup. The pressure is increased until deformation or burst of the line occurs. At that point, the pressure is noted.

Test Results

According to MIL-F-3836 3B (USAF) the fuel system and its components, excluding the vent and the refueling subsystems, shall be designed for an operating pressure of 60 psi; a proof pressure of 120 psi without malfunction, failure, permanent distortion, or external leakage; and an ultimate pressure of 180 psi without external leakage. The proof and ultimate pressure of the vent subsystem shall be two and three times the operating pressure, respectively. The refueling subsystem shall be designed for an operating pressure of 120 psi, a proof pressure of 180 psi, and an ultimate pressure of 240 psi.

In an actual burst test, the pressure was gradually increased to up to 240 psi. All the test lines described above were exposed to 240 psi pressure and no changes or deformations of the lines were noted. Thus, all the lines passed the burst test successfully.

2. Collapse Pressure Test

a. Test Setup Used

The test setup used here was the same as the one used for the burst pressure tests.

b. Procedure of Test

- Mount the line to the setup as shown in Figure 52. To obtain a tight seal at both ends of the line, rubber stoppers are used.
- Connect the vacuum pump hose to the setup and gradually pull the vacuum. The pressure drop is measured with a manometer.

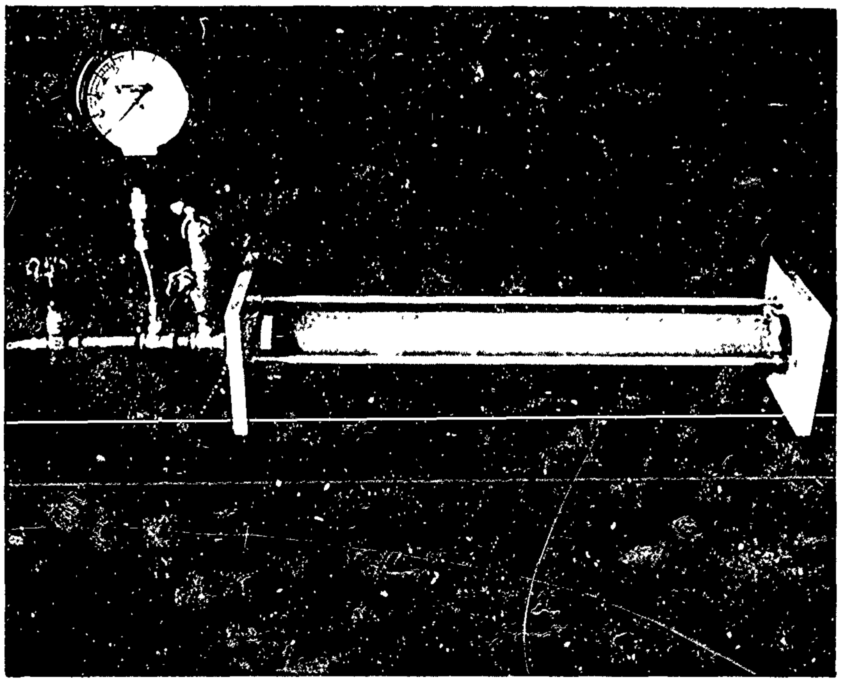


FIGURE 52. BURST AND COLLAPSE PRESSURE TEST SETUP

Test Results

The lines in (c), (d), (e), (f), and (g) described above resisted a high vacuum (≈29.5 inches of Hg). No changes or deformations of the lines occurred. The line configuration (a) started to deform or collapse at 17 inches of Hg and the line configuration (b) started to deform or collapse at 19 inches of Hg.

E. HYDRAULIC RAM EFFECT

The action of a penetrating projectile (.30 caliber AP) through a fuel line filled with a fluid was captured by high-speed photography. This was accomplished by using an acrylic (transparent) line measuring 24 inches long and having a 2½-inch I.D. This line was mounted to the fuel line test setup with water flowing through the line at an initial 35 psi pressure. The phenomena taking place inside the line when the projectile traverses was captured by the film before the acrylic line broke. The analysis of the film indicates that the projectile does not have time to tumble while traveling through 2½ inches of water after impacting the line in a 90° angle of incidence and 0° yaw. The projectile entered in a straight position and exited in a straight position. The cavitation formed behind the projectile traversing the water is cylindrical. The pressure generated was of large magnitude and appears to be concentrated on the wall area around the point of impact.

SECTION III

SUMMARY AND CONCLUSIONS

1. The objective of this program was the development of new and improved lightweight self-sealing fuel line composites that reliably seal wounds inflicted by .30 and .50 caliber AP projectiles.

2. The types of fuel lines evaluated under this program were:

a. Aluminum fuel line tubing 0.028 inches thick based on aluminum alloy 6061-T4-AL.

b. Laminated aluminum foil fuel lines based on 1100-0 (essentially pure aluminum) and 5052-H38 (an aluminum alloy) using flexible to rigid adhesive materials as interlaminar bonding agents.

c. Integrated aluminum foil fabric or compressed foam reinforced fuel line composites wherein a ply of ballistic nylon or natural rubber foam is interspersed between plies of aluminum foil bonded together using a flexible adhesive material as the interlaminar bonding agent.

d. Plastic laminated ballistic nylon or PRD-49 fabric reinforced fuel line composites impregnated with various epoxy resin sealant/adhesive binders.

3. Plastic fuel lines fabricated using 2 to 4 plies of ballistic nylon or PRD-49 impregnated with the epoxide resin adhesive binders suffered the least damage when punctured by .30 caliber projectiles. Damage to the entry wall was a small hole. On exiting, the projectile produced slit wounds 1/2 to 1 inch in length and caused the fabric to fray. The extent to which fraying occurred decreased as the ratio of epoxy resin to polyamide curing agent was adjusted to yield a more flexible fuel line composite. Results of these tests indicated ballistic nylon to be superior to PRD-49 as a fabric reinforcing component.

4. The laminated aluminum foil fuel lines suffered less damage than those prepared using aluminum foil 1100-0 which is essentially pure aluminum. A ply of ballistic nylon bonded to the inside and outside of the laminated aluminum foil fuel line was found to be sufficient for limiting the damage to sealable size wounds.

5. The damage caused by .30 and .50 caliber projectiles to the entry wall of a standard 28 mil thick aluminum fuel line tubing was limited to holes about the size of the projectile. On exiting the projectile punctured relatively large holes and tore the metal causing it to petal outward (flower) extensively. Applying 2 to 4 plies of ballistic nylon

impregnated with the 898 polysulfide sealant to the outer surface of a standard aluminum fuel line was effective in reducing overall damage but did not entirely eliminate flowering.

6. The compressed foam sealant concept proved to be effective for providing self-sealing protection. The plastic laminated fuel line protected by a 1/4 inch thick layer of natural rubber foam held in a compressed state by an outer ply of ballistic nylon impregnated with polysulfide sealant 898 successfully sealed wounds inflicted by .30 and .50 caliber projectiles. This self-sealing plastic fuel line composite weighs 0.83 lbs./ft^2, a third of the weight (2.59 lbs.ft^2) of a standard aluminum fuel line shielded by a .50 caliber natural rubber gum fabric reinforced self-sealing protective cover.

7. Similar test results were obtained with self-sealing integrated aluminum foil compressed foam, fabric-reinforced fuel line composites. The lightest weight self-sealing fuel line composite of this type fabricated that demonstrated a self-sealing capability at the .50 caliber projectile threat level weighed approximately 1.11 lbs./ft^2.

8. A composite comprised of a 1/4 inch thick layer of precompressed natural rubber foam sandwiched between plies of ballistic nylon fabric impregnated with polysulfide sealant 898 was evaluated as a protective cover for standard aluminum fuel line tubing. It proved to be effective for controlling damage and sealing wounds at the .30 caliber level of threat but not at the .50 caliber projectile threat level.

9. Hydraulic and vacuum pressure tests were performed on both the laminated aluminum foil and the plastic fuel lines with and without inner and outer protective plies of ballistic nylon impregnated with polysulfide sealant 898. Results of hydraulic pressure tests showed all of the laminated fuel line composites to be capable of withstanding pressures up to at least 240 psi without deforming. The plastic fuel line composite and the laminated aluminum foil fuel line composites prepared using an epoxy adhesive did not deform when subjected to a hard (29.5 inches of Hg) vacuum. Laminated aluminum foil fuel lines with and without an inner and outer protective ply of ballistic nylon fabricated using polysulfide 898 as the impregnating sealant and interlaminar bonding agent began to collapse when subjected to partial pressures of 19 and 17 inches of Hg, respectively.

SECTION IV

RECOMMENDATIONS AND FUTURE WORK

1. Continue the development of protection systems and self-sealing systems for preventing rupturing and flowering of semi-metallic and plastic fuel lines. Emphasis should be put on optimizing the laminated aluminum foil fuel lines and plastic fuel lines for weight, thickness, and efficiency against .50 caliber AP projectiles either impacting in a 90° angle of incidence and 0° yaw or in a tumbled condition and against .60 caliber projectiles.

2. The above systems should be evaluated for use against the higher threat projectiles and new or improved protection and self-sealing systems should be investigated and developed.

3. Curved laminated aluminum fuel lines and curved plastic fuel lines should be fabricated and evaluated.

4. Laminated aluminum fuel lines joints and plastic fuel lines joints should be fabricated and evaluated.

5. The unprotected and protected fuel lines developed should be evaluated against high explosive projectiles exploded in air and in fuel.

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