FOREWORD/ACKNOWLEDGEMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI) San Antonio, Texas at the request of Dr. Richard E. McClelland, U.S. Army TACOM. Funding for this program was provided by the DETO-STOP product sponsor. This program was conducted during the period of April-June 1998.

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I. INTRODUCTION

Fuel tank fires and explosions due to ballistic impacts have been a major concern of the DoD for many years. Over the years there have been many attempts to reduce or eliminate the disastrous effects that result from a ballistic impact on a fuel cell containing hydrocarbon fuels. The sequence of events when a ballistic round penetrates a fuel tank can be described as follows:

Ballistic impact resulting in fuel cell penetration and internal explosion. Round penetration can occur either in the vapor space or below the fuel liquid level. If there is a flammable mixture in the vapor space, a vapor explosion can occur that causes overpressure inside the tank and burning fuel to blow out of the inlet and exit holes. Greater damage to the fuel cell can result from an impact below the liquid level, which causes a vapor space explosion and also very destructive hydraulic ram effects. Upon impact, the energy from the projectile is transformed into kinetic energy generating a pressure pulse in the liquid, that impinges upon the side (or end) of the fuel cell. It is generally believed that the hydraulic ram effects cause the major damage to the fuel cell. This impact-induced fluid pressure may result in a more extensive rupture of the fuel tank, more rapid dispersal of fuel, a large mist fireball and instantaneous pool burning.

II. EXPERIMENTAL PROCEDURE

This program was undertaken at the request of U.S. Army TARDEC in order to take advantage of the extensive experience and facilities available at TARDEC. These facilities include a ballistic range and assorted support equipment such as the 20 mm Mann barrel and HEIT ammunition. These facilities were available on a non-interference basis since they are also used to support other DoD fuel and hydraulic fluid developmental programs. Additionally, there is also available extensive experience from the laboratory staff members, who conducted similar ballistic tests on "EXPLO-SAFE", aluminum foam, during the 1980's. This testing will be discussed later in this report.

A. Test Targets

A series of four ballistic tests were conducted during this evaluation. All tests were conducted using 30 gallon drums as the fuel cells. These drums were equipped with removable lids to allow the introduction of the metallic foam, DETO-STOP.

For each test, a section of 1/4" aluminum armor plate was positioned in front of the target drum and acted as an activator plate for the Heit round. The plate was angled at 45° from vertical. Impact of the 20-mm HEIT round on the armor plate test the effects of the spall impacting the target drums.

Test 1 (Drum A) - This test was conducted with a drum filled with DETO-STOP. The plan called for the first shot to be fired into the vapor space above the ullage. Only 10 gallons of fuel were placed into the drum, making it easier to target the vapor space.

Test 2 (Drum C) - There was no DETO-STOP in this test fixture. Otherwise, the test set-up and procedures were identical to Test 1.

Test 3 (Drum B) - This test fixture was filled with DETO-STOP. The plan called for this shot to be fired into the liquid-filled space. Twenty gallons of fuel was placed into the drum, making it easier to target the liquid.

Test 4 (Drum D) - There was no DETO-STOP in this test fixture. Otherwise, the test set-up and procedures were identical to Test 3.

B. Test Fuel

JP-8 fuel was chosen as the fuel for all tests, as this is representative of the diesel type fuel used in U.S. Army vehicles. However, JP-8 has a flashpoint of 122°F. The flashpoint of a fuel is the temperature at which fuel vapors are given off that will ignite if exposed to an ignition source. As the intent of Tests 1 and 2 was to investigate explosions in the vapor space, the fuel needed to be above its flashpoint. This could have been accomplished by heating the fuel to a temperature greater than 122°F, or by blending a small amount of fuel with a low flashpoint.

It was decided to blend two percent (by volume) gasoline to reduce the flashpoint to approximately 72°F. As the ambient temperature that day was approximately 85°F, the fuel blend provided sufficient vapor in the vapor space to ignite if exposed to an ignition source.

The JP-8/gasoline blend was used only for Tests 1 and 2. Conventional JP-8 was used for Tests 3 and 4.

III. BALLISTIC FACILITIES

This series of four ballistic tests was conducted at Southwest Research Institute using the U.S. Army TARDEC Fuel and Lubricants Research Facility ballistic range. This facility includes a concrete target bunker with three walls and a roof. The bunker has dimensions of approximately 10 feet wide, 9 feet high and 10 feet deep. The concrete floor is sloped forward to allow collection of the fuel for proper disposal.

The ammunition used was a 20-mm HEIT fired from a Mann Test Barrel. The velocity of these bullets was not chronographed. The ballistic events were documented using real-time video and 200-frames/second 16-mm film. Stop action still photos from impact are shown in Figures 1-4. These photos illustrate the variation in size of fireball and pool burning at various times after impact.

IV. SUMMARY OF RESULTS

A. Fuel Response

The high speed (200 FPS) 16mm film at TARDEC (SwRI) was difficult to interpret and not conclusive. The high-speed footage seemed to instantly capture the formation of smoke, which obscured the frame-by-frame fireball development. Frame by frame analysis of the VHS video, however, gave a much clearer picture of the actual ballistic impact-fuel response.

Figures 1-4 will be reviewed to clearly describe the development of the fireball and pooling fires occurring post impact.

Figure 1 shows a series of frames recorded immediately after impact of the target drum containing 10 gallons of fuel and DETO-STOP. Note that at approximately **one** second after impact, the fireball disappeared and the fire appeared to be extinguished. This is clearly shown in the one-second frame followed by a small pooling fire beginning at approximately two seconds after impact.

Figure 2 shows a series of frames recorded immediately after impact of the target drum containing 10 gallons of fuel, and no DETO-STOP. The impact into the vapor space formed a fireball that continued into pool burning. Also shown in this series, is an internal fuel tank fire that became a secondary explosion at approximately two seconds after impact. This secondary fireball appeared to enhance the development of a larger fireball and more rapid development of pool burning. This was apparently created by the vacuum formed when the fire consumed all of the air in the tank, which sucked additional air into the heated target vessel.

Figure 3 shows a series of frames recorded immediately after impact of the target drum containing DETO-STOP and 20 gallons of fuel. The ballistic impact was below the liquid level. The fireball that developed appears to be subdued as shown in the one and two second frames after impact. This is probably due to the fact that the drum was not ruptured by the hydraulic ram and, therefore, fuel spillage rate was reduced. This may be due to the DETO-STOP mesh absorbing the shock from the ballistic round.

Figure 4 shows a series of frames recorded immediately after impact of the target drum containing 20 gallons of fuel and not containing DETO-STOP. The impact was below the liquid fuel level. It is obvious that immediately after impact, the fuel sprayed in all directions and immediately developed into pool burning and at one second after impact there was already developed a large pool fire. When comparisons are made between Figure 14 and Figure 15, it does appear that the pool burning was more intense from the target without DETO-STOP. Referring to Figures 9c and 9d, the face of the drum without DETO-STOP was ripped open and this could explain the reason for the more intense pool burning that developed so quickly.

B. Target Response

This summary will utilize the pictures that are presented in Figures 5-15.

Figure 5 presents photographs of Drum A containing DETO-STOP and 10 gallons of fuel, showing the entry point (left photo) and the exit point (right photo). These tests were conducted to demonstrate vapor explosion damage from impacts in the ullage space. Results that were documented on the video indicate a fireball upon impact and a small pooling fire. *Figure 6* includes side angle photographs and indicates very little drum distortion from overpressure, in the drum with DETO-STOP.

Figure 7 presents photographs from the entry and exit of the ballistic round. These photographs are from Drum C that did not contain DETO-STOP and had 10 gallons of fuel. As with Drum A, this ballistic impact was also into the ullage space in order to investigate the effects of vapor phase explosions. *Figure 8* are photographs taken from the side that indicates drum distortion on the exit end of the target. When comparing Figures 6 and 8, it is obvious that there was more overpressure in the drum without DETO-STOP. Measurements were not taken to document the actual pressures within the two targets.

Figure 9 illustrates the drum containing DETO-STOP and 20 gallons of fuel. The ballistic impact was below the fluid level. *Figure 10* is a side-angle shot that shows the drum distortion that is presumed to be due to the hydraulic ram effect. Note that the target drum was not ripped open.

Figure 11 illustrates the results of the ballistic impact with a target containing 20 gallons of fuel and no DETO-STOP. ***Figure 12*** is a side angle photo showing target distortion, probably due to increased hydraulic ram effect. Better comparisons are illustrated in ***Figure 13***. These photographs (13a) versus (13b) indicate increased overpressure within the drum without DETO-STOP. Also, (13c) and (13d) shows greater target damage to the fuel cell without DETO-STOP.

Figures 14 and 15 are photographs of the DETO-STOP from Drums A and B. Drum A was the test that was conducted to evaluate the vapor explosion suppression. The appearance of test was somewhat different in that the vapor explosion showed a different burn pattern than did the shot below the liquid level. The DETO-STOP from these two tests was somewhat different in that the material from the vapor explosion. Figure 14 shows evidence of more uniform burning occurring in the vapor space of Drum A, whereas Drum B showed that the projectile was stopped without exiting, and the metallic foam still maintained its integrity.

V. DISCUSSION OF RESULTS

Although only a limited number of ballistic tests were conducted, we believe the results are valid. A reduction in the mist fireball and pool burning that was observed with the drums equipped with DETO-STOP. This is due, we believe, to the fact that there was less pressure build-up in the tanks containing DETO-STOP. The lower pressure build-up is consistent with less target distortion and lower fuel spillage rates and fuel spray reduction. These factors could be very important in an integrated system to reduce the fuel fire hazard for the following reason.

After many years of research to find a replacement for the Halon 1301 suppression system, it is obvious that an equal replacement agent will be difficult to find. Therefore, less effective systems will probably be employed and, thus, increase the fuel fire hazard in armored ground equipment. When flammability testing is conducted, one very important parameter is time. The sooner a fire can be detected and treated, the easier it is to extinguish. If the size of the fireball is suppressed for a period of time, the suppression system could be more effective in extinguishing the fire. From these limited ballistic tests, the use of DETO-STOP may provide valuable enhancement to the existing fire suppression systems.

Appendix A is a copy of a report of testing conducted at this laboratory on the aluminum foil EXPLO-SAFE from the early 1980's. According to the developer, this material would reduce the severity of a ballistic impact on a fuel cell by reducing the overpressure build-up and thus the damage from the hydraulic ram effects. ***Figure 3*** (Appendix A) shows two target drums, one containing EXPLO-SAFE and the other without EXPLO-SAFE. Results of these tests indicated that the two target drums suffered similar overpressure (hydraulic ram effects). Comparison of these results with those targets evaluated with DETO-STOP indicated that there was a reduction in target damage resulting from hydraulic ram effects due to the DETO-STOP material. Comparison of the target damage from this series of tests of the drum without DETO-STOP was most similar to the EXPLO-SAFE tests, i.e.; face of the target was ripped open from the hydraulic ram effects. It appears that DETO-STOP is more rigid and, thus, more effective in absorbing the kinetic energy from the ballistic impact.

FIGURE 1

U.S. ARMY TARDEC
FUELS AND LUBRICANTS RESEARCH FACILITY (SwRI)
BALLISTIC EVALUATION OF DETO-STOP
March 25, 1998

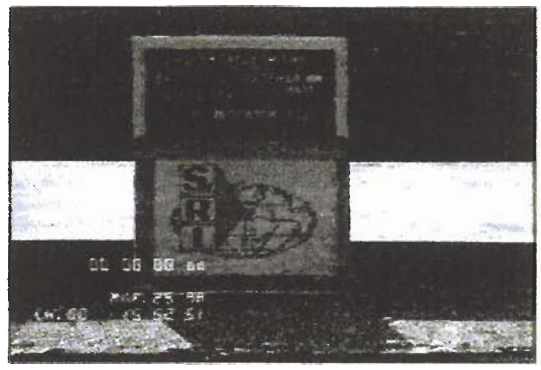
<u>TEST ONE</u>

20mm HEIT into 30 gal. Drum A

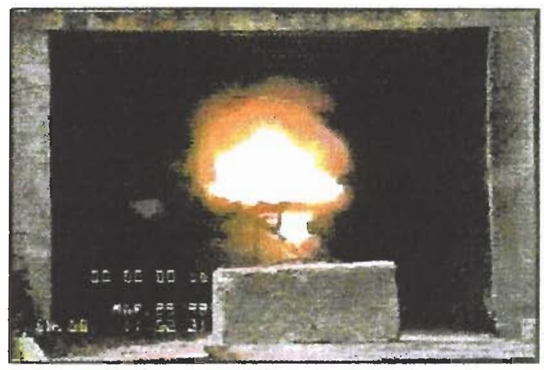
10 gal JP-8 with 2% AVGAS

<u>WITH</u>

DETO-STOP MESH



TYPICAL CONFIGURATION
(1/4" ARMOR PLATE @ 45°)



AT IMPACT

AT 1 SECOND

AT 2 SECONDS

FRAMES CAPTURED FROM SwRI TEST VIDEOTAPE
SHOWING BALLISTIC TESTING <u>WITH</u> DETO-STOP.

FIGURE 2

U.S. ARMY TARDEC
FUELS AND LUBRICANTS RESEARCH FACILITY (SwRI)
BALLISTIC EVALUATION OF DETO-STOP
March 25, 1998

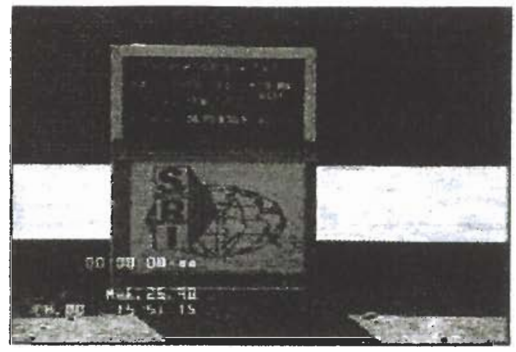
<u>TEST TWO</u>

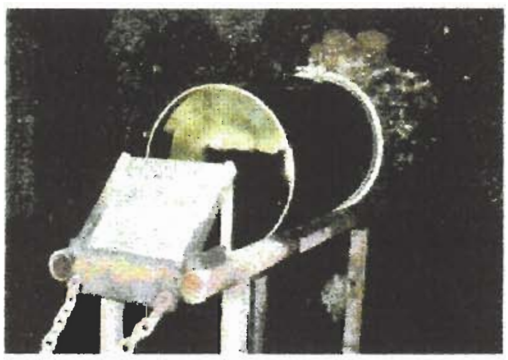
20mm HEIT into 30 gal. Drum C

10 gal JP-8 with 2% AVGAS

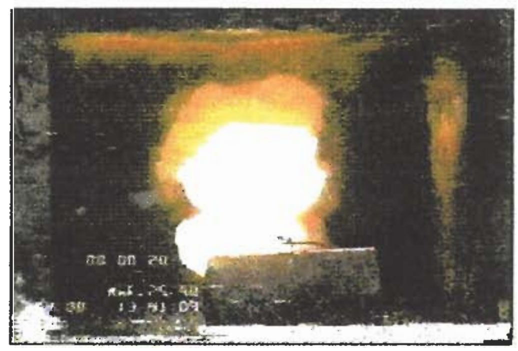
<u>WITHOUT</u>

DETO-STOP MESH





TYPICAL CONFIGURATION
(1/4" ARMOR PLATE @ 45°)



AT IMPACT

AT 1 SECOND

AT 2 SECONDS

FRAMES CAPTURED FROM SwRI TEST VIDEOTAPE
SHOWING BALLISTIC TESTING <u>WITHOUT</u> DETO-STOP.

FIGURE 3

U.S. ARMY TARDEC
FUELS AND LUBRICANTS RESEARCH FACILITY (SwRI)
BALLISTIC EVALUATION OF DETO-STOP
March 25, 1998

<u>TEST THREE</u>

20mm HEIT into 30 gal. Drum B

20 gal JP-8

<u>WITH</u>

DETO-STOP MESH

TYPICAL CONFIGURATION
(1/4" ARMOR PLATE @ 45°)

AT IMPACT

AT 1 SECOND

AT 2 SECONDS

FRAMES CAPTURED FROM SwRI TEST VIDEOTAPE
SHOWING BALLISTIC TESTING <u>WITH</u> DETO-STOP.

FIGURE 4

U.S. ARMY TARDEC
FUELS AND LUBRICANTS RESEARCH FACILITY (SwRI)
BALLISTIC EVALUATION OF DETO-STOP
March 25, 1998

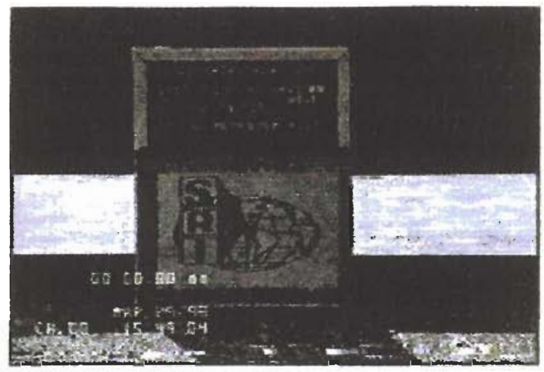
TEST FOUR

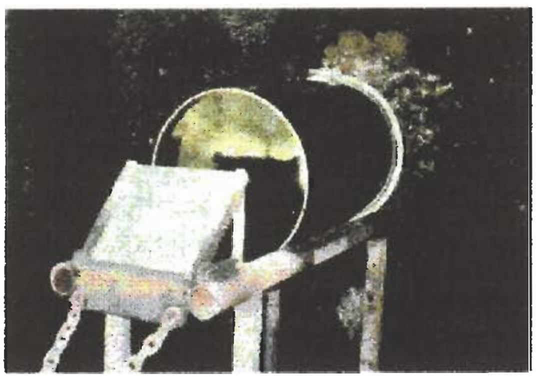
20mm HEIT into 30 gal. Drum D

20 gal JP-8

WITHOUT

DETO-STOP MESH





TYPICAL CONFIGURATION
(1/4" ARMOR PLATE @ 45°)

AT IMPACT

AT 1 SECOND

AT 2 SECONDS

FRAMES CAPTURED FROM SwRI TEST VIDEOTAPE
SHOWING BALLISTIC TESTING WITHOUT DETO-STOP.

Figure 5. Head-On View of Drum w/DETO-STOP; 10 Gallons Fuel

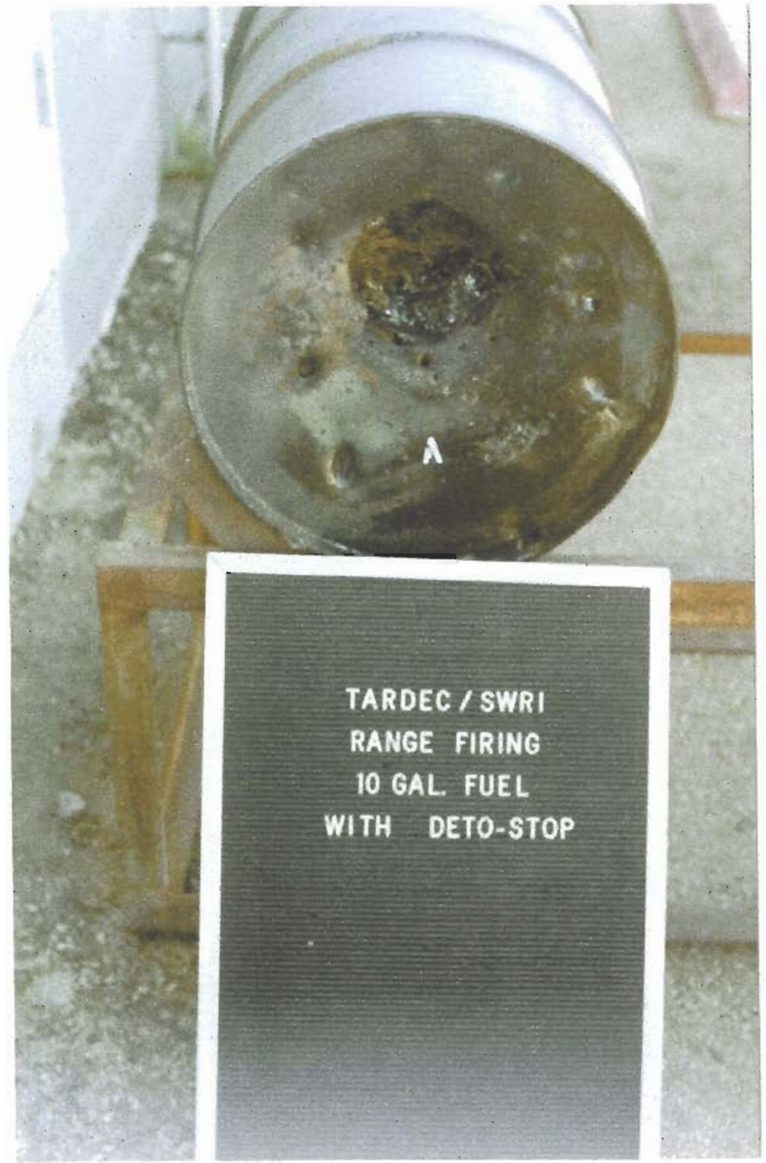


Figure 6. Side View to Show Drum Distortion; 10 Gallons Fuel

Figure 7. Head-On View of Drum w/out DETO-STOP; 10 Gallons Fuel

Figure 8. Side View to Show Drum Distortion; 10 Gallons Fuel

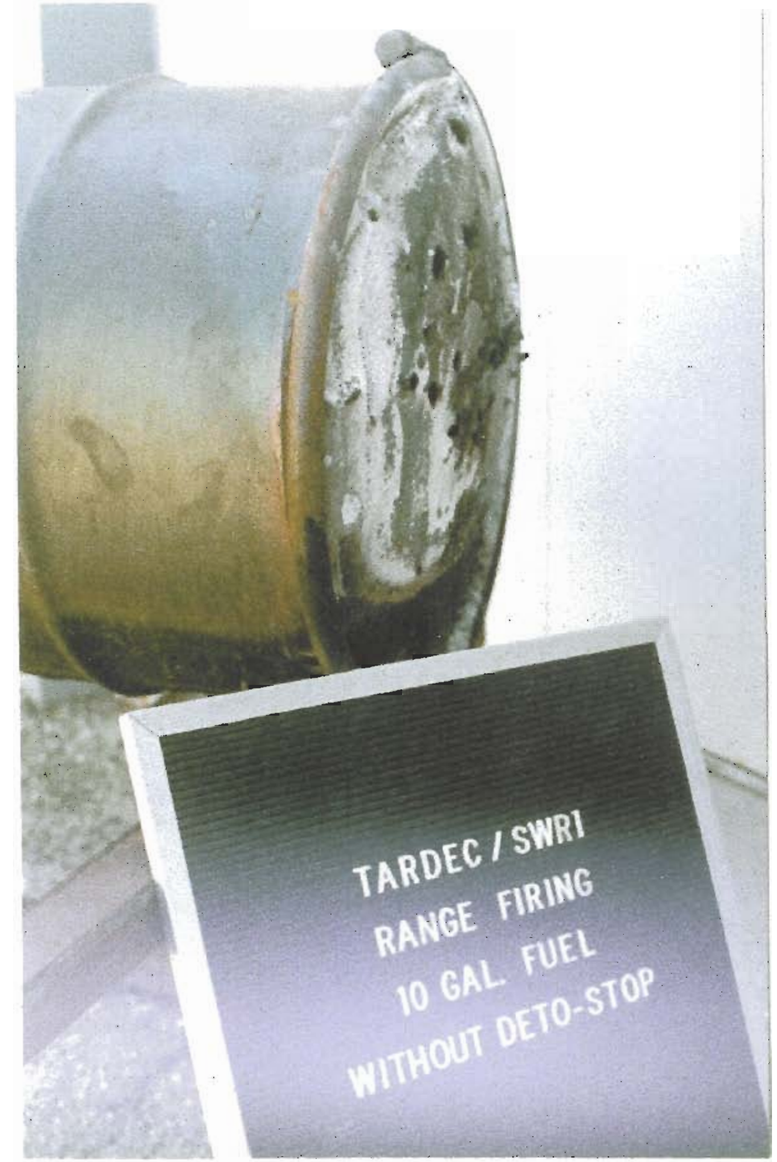


Figure 9. Head-On View of Drum w/DETO-STOP; 20 Gallons Fuel

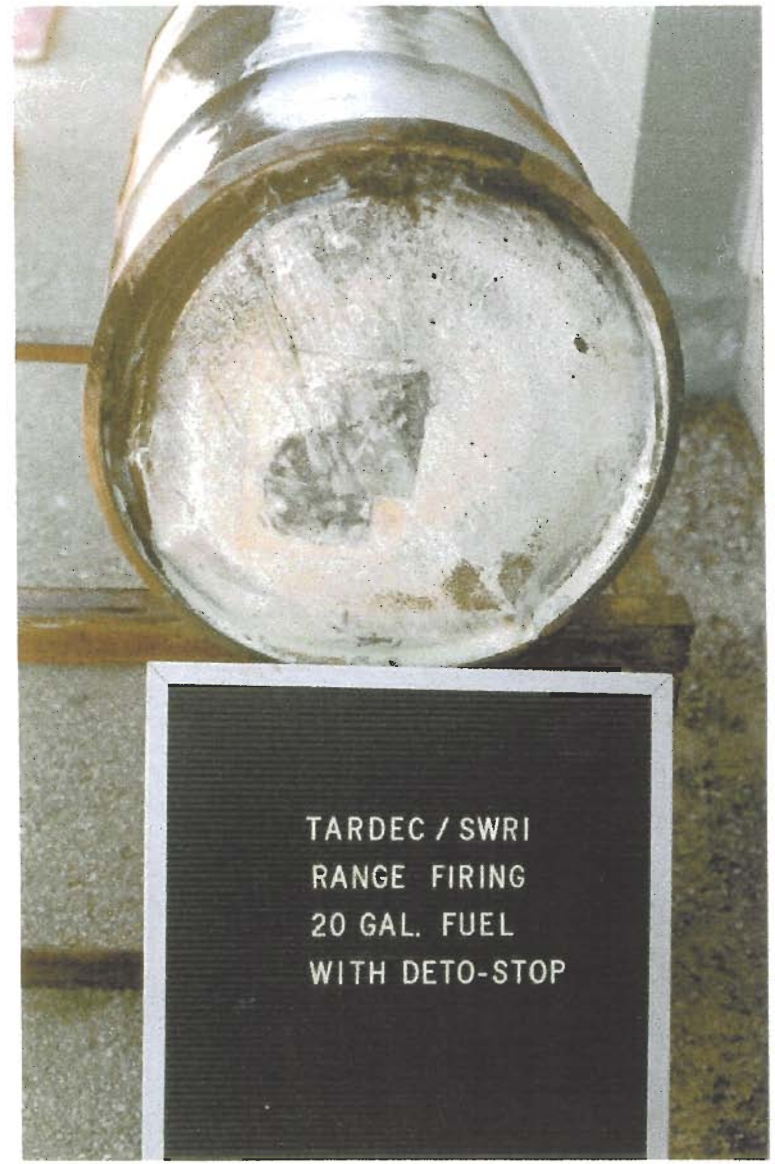


Figure 10. Side View to Show Drum Distortion; 20 Gallons Fuel

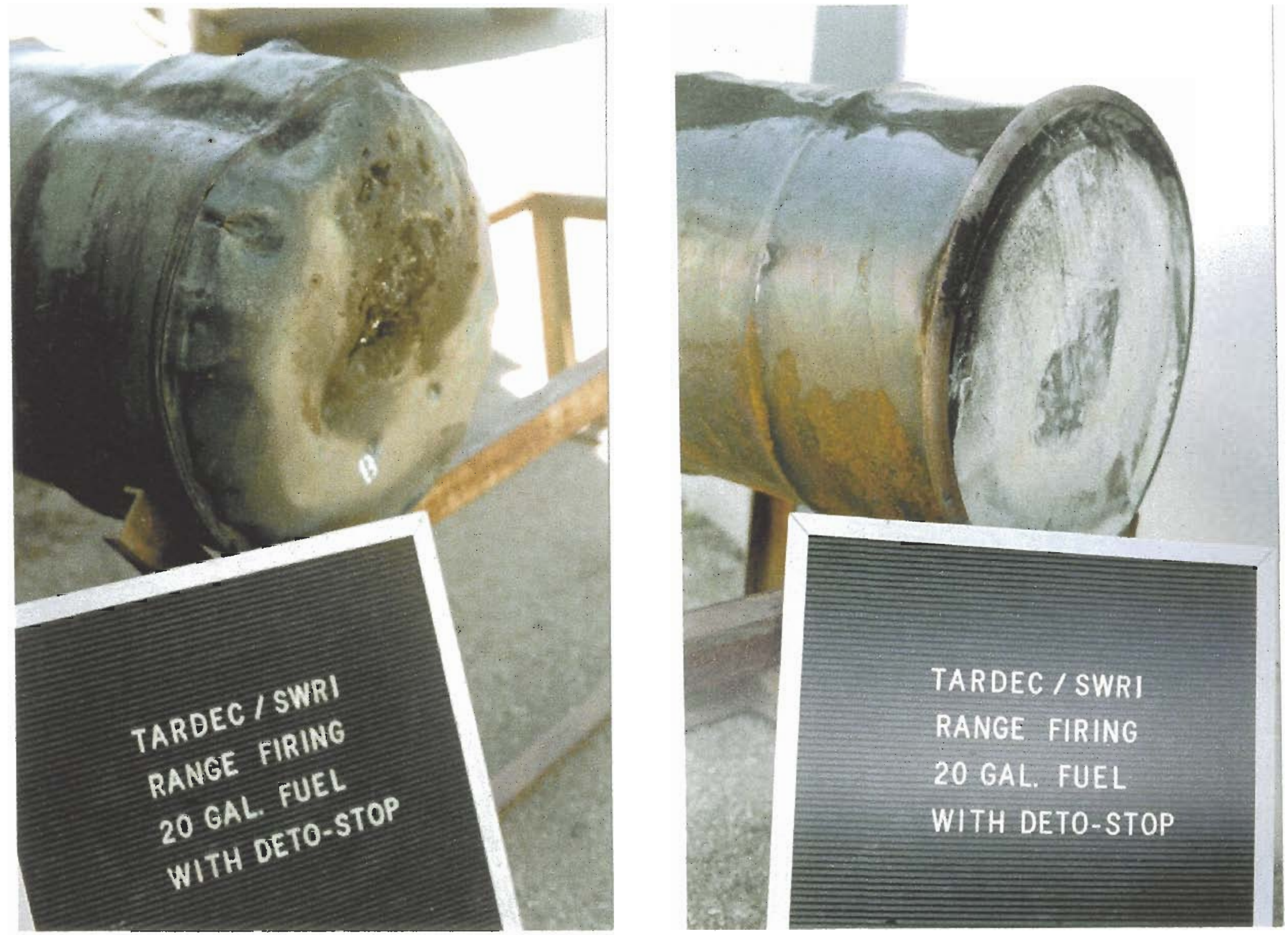


Figure 11. Head-On View of Drum w/out DETO-STOP; 20 Gallons Fuel

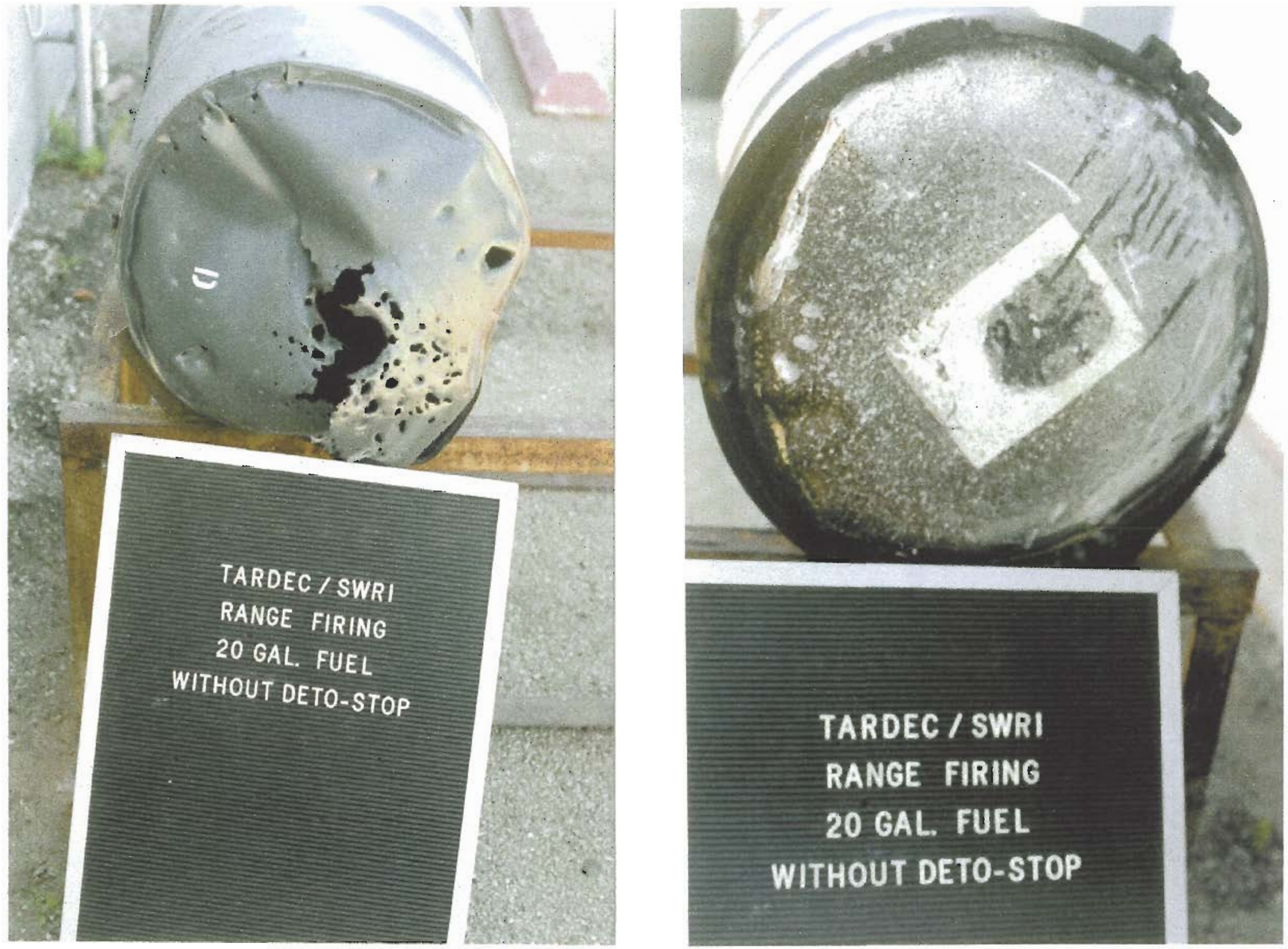
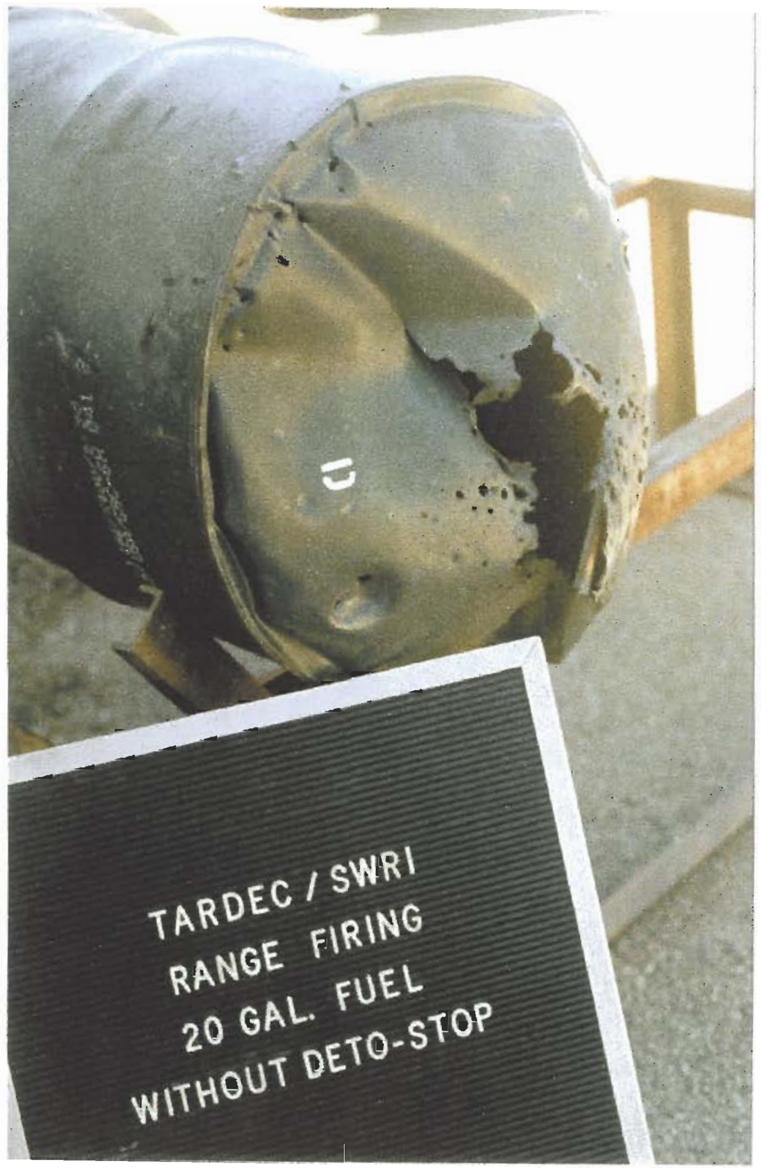


Figure 12. Side View to Show Drum Distortion; 20 Gallons Fuel



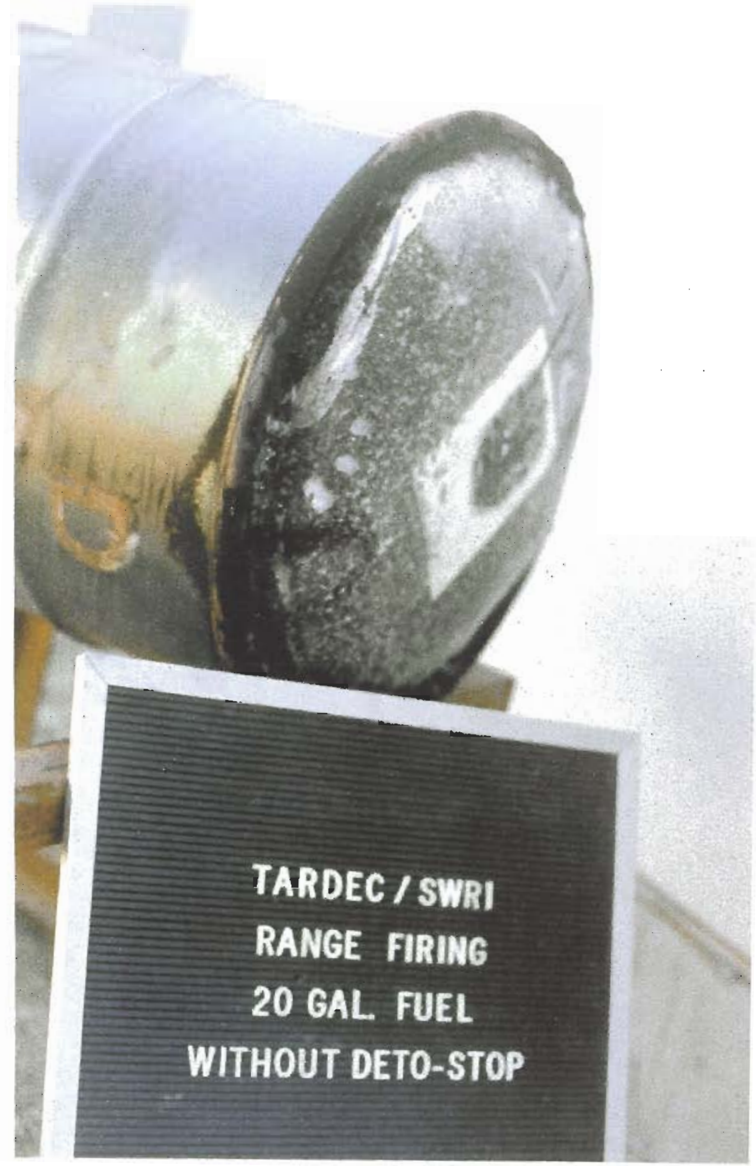


Figure 13. Side by Side Comparisons of Drum Distortion

13a, 10 Gallons w/out D.S.

13b, 10 Gallons w/D.S.

13c, 20 Gallons w/D.S.

13d, 10 Gallons w/out D.S.

Figure 14. DETO-STOP from Vapor-Space Ballistic Test; 10 Gallons

Figure 15. DETO-STOP from Liquid Level Ballistic Test; 20 Gallons

APPENDIX A.

TESTING ON ALUMINUM FOIL EXPLO-SAFE

APPENDIX A.

MEMORANDUM 15 July 1981

FROM: AFLRL Fluid Fire Safety Section

TO: F.W. Schaekel, DRDME-GL

SUBJECT: Simulated Full-Scale Ballistic Tests of Explosafe in Simulated Diesel Fuel Tanks Under Realistic Exposure Conditions

The proprietary Canadian product Explosafe was brought to the attention of MERADCOM and AFLRL personnel via presentations by its manufacturer, Vulcan Industrial Packaging, Ltd., before the Aviation Fuel System Safety Group of the Aviation Committee of the Coordinating Research Council (CRC) in November 1975. In 1976, the U.S. Air Force initiated discussions with the Canadian government to obtain sufficient quantities of Explosafe for an in-depth investigation of its potential efficacy for fire/explosion supression within aircraft fuel tanks as a substitute for reticulated foams.

The Air Force interest stemmed from the demonstrated capability of Explosafe to prevent or diminish explosions within the vapor space of vessels containing explosive concentrations of hydrocarbons. The results of the USAF studies have been documented in several reports.

Experimental ballistic testing of Explosafe was initiated at AFLRL in August 1977 using 20 mm HEIT rounds fired into 114-liter fuel tanks below the surface of 76 liters of liquid fuels. These simulated full-scale fuel tanks are illustrated in Figure 1. The drums were provided by AFLRL and filled with Explosafe gratis by the manufacturer's representative, Explosafe America, Inc. Results of the initial test with DF-2 diesel fuel at 77°C indicated that Explosafe had little or no effect on pool burning. The 77°C temperature corresponds to fuel temperatures experienced in U.S. Army combat vehicles due to the use of fuel as a coolant for fuel injectors. A repeat test was conducted using a fuel cell slightly different from the first; however, the same results were observed with both fuel cell configurations. These test results and copies of "before and after" photographs were transmitted to MERADCOM.

Properties of the base fuel used to evaluate Explosafe are listed in Table 1. Table 2 describes the results obtained. Evaluation of the fuel response to ballistic penetration indicated a reduced mist fireball with Explosafe but no significant change in pool burning characteristics. Benefits of the diminished fireball, if any, could not be established by the limited number of tests conducted. Pool burning resulting from the fuel spill, as shown in Figure 2, showed no significant difference with and without Explosafe. Figure 3 illustrates that the fuel tank distortion and rupture caused by hydraulic ram effects was not significantly altered by the presence of Explosafe.

The results of these ballistic tests conducted at AFLRL provided strong evidence that no substantial combat fire vulnerability reduction would result from the use of expanded aluminum foil in the fuel tanks of diesel-powered ground equipment under anticipated exposure conditions where the fuel temperature exceeds the fuel flash point. Accordingly, no further investigations of Explosafe were conducted.

TABLE 1. PROPERTIES OF DF-2 USED IN AFLRL SIMULATED FULL-SCALE BALLISTIC TESTS OF EXPLOSAFE

Flash Point, °C	58
Pour Point, °C	-2
Specific Gravity (16°C)	0.86
Existent Gum, mg/dl	7
Ash, wt%	0.001
Carbon Residue, wt%	0.2
Total Acid No. mg KOH/g	0.04
Accelerated Stability, mg/dl	0.8
Copper Corrosion Rating	1A(NIL)
Viscosity, cSt	
77°C	1.75
38°C	3.47
0°C	10.3
-2°C	11.2

TABLE 2. RESULTS OF AFLRL SIMULATED FULL-SCALE BALLISTIC TEST OF 76 LITERS OF DF-2 FUEL IN 114-LITER EXPLOSAFE -CONTAINING DRUMS AT 77°C(170°F)

Target Response	Effect of Explosafe
HEIT Fragments Totally Contained Within Fuel Tanks--Only Front Face Perforated	No Significant Change
Perforated Front Face of Tank Bulged Outward and Separated From Drum Over About 80% of Its Perimeter and Front Bottom of Tank Ruptured	No Significant Change
Transient Fireball Engulfed Fuel Tank	Reduced Size of Fireball
Intense And Sustained Ground Fire Enveloped Fuel Tank	No Significant Change

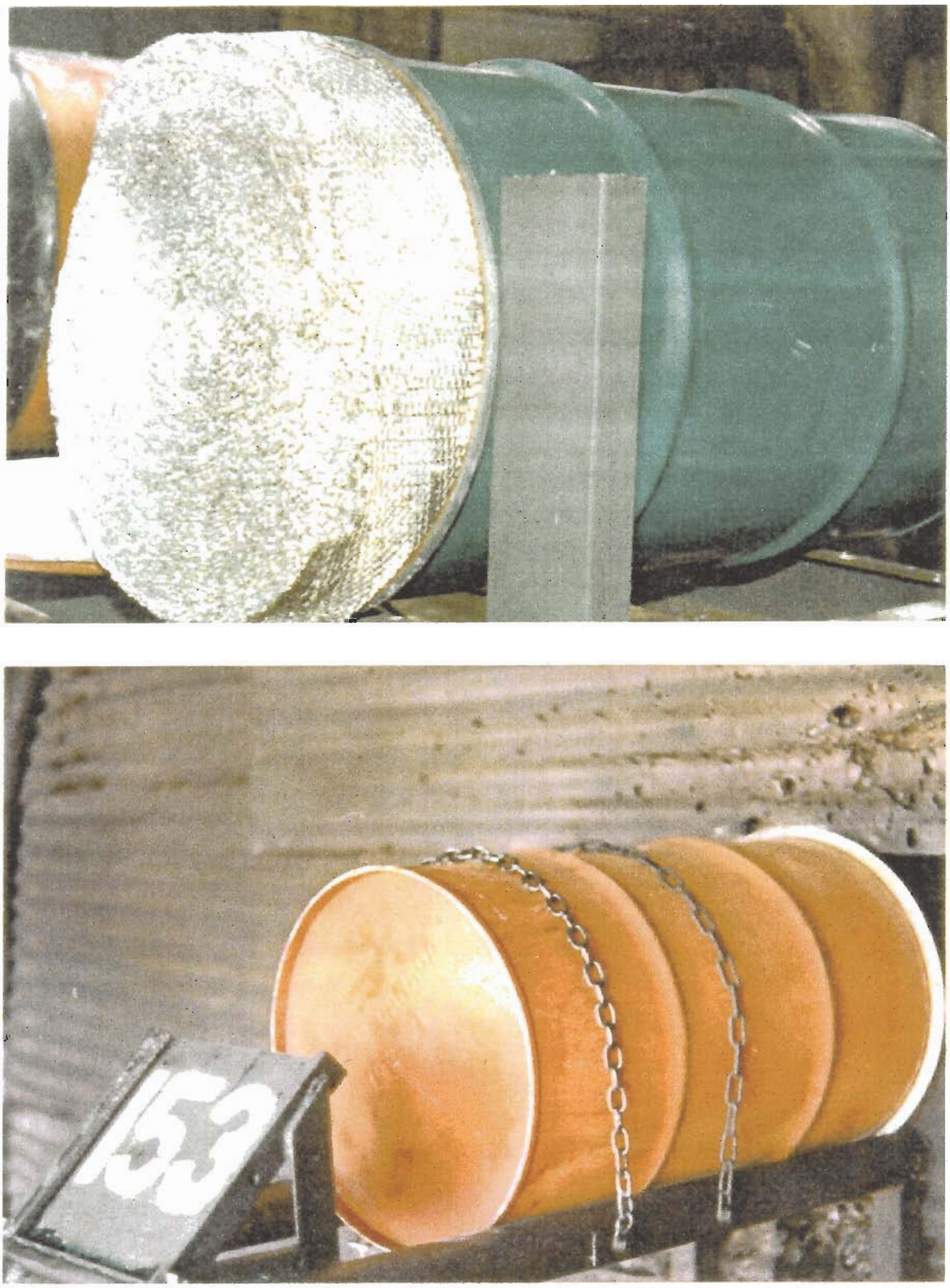


FIGURE 1. PHOTOGRAPHS OF EXPLOSAFE-CONTAINING 114-LITER DRUMS USED IN AFLRL SIMULATED FULL-SCALE BALLISTIC TESTS

Control Test

Test With Explosafe-Containing Drum

FIGURE 2. GROUND FIRES OBSERVED IN AFLRL SIMULATED FULL-SCALE BALLISTIC TESTS OF EXPLOSAFE WITH DIESEL FUEL At 77°C (170°F)

FIGURE 3. PHOTOGRAPHS ILLUSTRATING NEAR–IDENTICAL HYDRAULIC RAM RUPTURE EFFECTS OF 76 LITERS OF DIESEL FUEL IN 114-LITER DRUMS WITH AND WITHOUT EXPLOSAFE IN AFLRL SIMULATED FULL-SCALE BALLISTIC TEST