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SPILLED FUEL IGNITION SOURCES AND COUNTERMEASURES

N. Johnson, et al

Ultrasystems, Incorporated

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16 Abstract

This program defined the conditions under which motor vehicle crash fires are ignited and proposed practible countermeasures to reduce the incidence of these fires. Both ignition sources and fuel spillage were investigated.

It was determined that electrical sparks generated from damage to the vehicles's electrical system during a crash are the most hazardous ignition sources. Vehicle headlight filaments are also effective ignition sources.

Full-scale crash tests demonstrated that commercially available inertia switches will shut off the vehicle's electrical system during frontal, front-to-rear, and rollover crashes. These switches, coupled with a plastic shield for the positive battery terminal, effectively eliminated all electrical ignition sources. Fuel system countermeasures were also developed which successfully prevented fuel spillage during high-speed front-to-rear crashes and rollovers.

A cost-benefit analysis showed that a combined ignition source and fuel spillage countermeasure system which would be 100 percent effective in eliminating crash fires would not be cost effective. An electrical countermeasure system would become cost effective within three years. However, it is estimated that this system would eliminate only 85 percent of the crash fires.

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1.0 INTRODUCTION

This report culminates a 13-month program structured to identify problem areas and propose modifications to automobiles in these areas which will reduce the rate of post-crash fires and their catastrophic results. Both fuel system and potential ignition sources were investigated.

This program was conducted for the National Highway Traffic Safety Administration under Contract DOT-HS-4-00872 entitled "Spilled Fuel Ignition Sources and Countermeasures." An important aspect of this program was to demonstrate, through the mechanics of crash testing, the type of fire safety protection that can be provided by present technology.

The program consisted of five major tasks which are described in the following paragraphs:

Task 1. State-of-the-Art Survey

This survey consisted of appraising and cataloging available books and articles which might be useful in defining the crash fire problem, fuel characteristics, available countermeasures, etc. This survey also provided the statistical information required to perform a cost/benefit analysis to determine which vehicle modifications would be most beneficial from a monetary basis.

Task 2. Definition of Ignition Source Conditions

A laboratory testing program was utilized to define conditions under which vehicle ignition sources present in crash situations would ignite spilled fuel and to determine which of the possible ignition sources were the most hazardous. Four types of sources were investigated: electrical, friction, heated surface, and open flame. The results of these tests were used to help define optimum countermeasure systems to provide the greatest protection at the lowest price.

Task 3. Baseline Test Program

A series of four crash tests was conducted during this program to establish baseline conditions for crash fires: a barrier test, two front-to-rear impact tests, and a rollover test. These tests provided available fuel and ignition sources at impact to insure that a fire would result. The same conditions which were set for fire in these crashes were used in the subsequent demonstration tests to prove that the countermeasures did indeed prevent fires. This was required for undeniable proof of the countermeasures' effectiveness since only a small percentage of all motor vehicle accidents results in fire. This series of tests also provided information which was used in the design and installation of countermeasure devices.

Task 4. Development of Countermeasure Systems

Based on the results of the previous tasks, a design and test program was conducted to develop effective countermeasures for preventing crash fires. Such items as fuel tank relocation, line routing, battery protection, and electrical system inerting were investigated, and designs drawn up to incorporate these modifications in the demonstration test vehicles. This part of the program also included testing of various inertia shutoff devices on the deceleration sled to determine their operating characteristics. Along with the development of the countermeasure systems, a cost/benefit analysis was performed to determine which protection system was most beneficial to the public on a cost basis.

Task 5. Demonstration of Developed Countermeasures

The final phase of the program demonstrated the effectiveness of the developed countermeasures in four crash tests. These four tests were identical to the baseline test series with one exception - countermeasures were installed in the vehicles to prevent a fire. In three of the tests either a fuel or electrical countermeasure system was installed. Therefore, if the system functioned properly, one item required for fire would be eliminated and a fire would not result. On the fourth test, the rollover, both systems were used together. These tests were designed to provide the same high risk of fire as the baseline tests, and if the countermeasure systems did not function, catastrophic fire would result.

This report presents a detailed description of the entire test program and the results achieved. Based on the determination of the specific vehicle fire hazards, countermeasures are recommended which are practicable for use in standard automotive vehicles both from production feasibility and cost aspects.

2.0 STATE-OF-THE-ART SURVEY

Although motor vehicle accidents are observed everyday throughout the country, a post-crash fire is seldom seen. Therefore, it may be easy to overlook that particular aspect of vehicle safety; however, when an accident of this nature does occur, the probability of survival is greatly reduced. Data have been collected to better acquaint the reader with the statistical nature of this problem, the type of vehicle components which contribute to fire hazards, and the available means to reduce the incidence of fire accidents. The bibliography at the end of this report indicates the material which was investigated for the program.

2.1 ACCIDENT STATISTICS

2.1.1 Fire Accident Statistics

A very difficult aspect of this program was determining the magnitude of the post-crash fire problem. Initial plans were to obtain fire accident statistics from the NHTSA data bank of nationwide accident statistics. However, data pertaining to motor vehicle crash fires were not available from this source. Therefore, all available reports in the literature pertaining to crash fire statistics were utilized to obtain a statistical data base from which to assess the magnitude of the fire problem on a nationwide basis.

An examination of these reports disclosed broad inconsistencies in the statistical data. These are undoubtedly due to the two distinct methods used to gather the data. Some of the reports have attempted to draw together data after the fact from police records, which, in many cases, have no reliable method of reporting vehicle fires. Those states which do report fires lack any standardization among themselves in the manner in which they report the data. On the other hand, several in-depth studies structured specifically to study the fire problem have been conducted. While these studies are probably more accurate and specific, they are based on extremely small sample sizes and are confined to one or two states, thus drawing in any bias that may be due to specific geographical areas.

Extrapolation of the data from both methods to nationwide projections is highly questionable and leads to quite different results. However, consideration of both sets of data does bracket the magnitude of the fire problem and furnishes some basis for conducting cost/benefit analyses on vehicle modifications to prevent crash fires. The following paragraphs discuss the available statistical data in some detail. The cost/benefit analyses are presented in Section 5.0.

Figure 2-1 shows a comparison of findings compiled by the University of Michigan in the HSRI Special Report, Fire in Motor Vehicle Accidents (Reference 1). The results of this survey illustrate the major divergence of opinion on projected national fatalities as well as the commonly encountered problem of distinguishing between fatalities in accidents accompanied by fire and fatalities resulting from fire alone. (The only method readily available to determine the latter is by examining death certificates to ascertain the actual cause of death.)

The first three studies listed in Figure 2-1 were not used to determine vehicle fire fatalities during this program. The Dunn and Halpin study was not used primarily because the data on which it was based was accumulated 26 years ago and is significantly higher than any of the more recent studies. The New York and Los Angeles studies were not used because they did not differentiate between fatalities accompanied by or resulting from vehicle fires.

The cross-hatched data in Figure 2-1 represent the estimated 1972 nationwide motor vehicle fatalities occurring as a direct result of burns. These projections were based on the percent of burn fatalities found during each survey. The bottom seven

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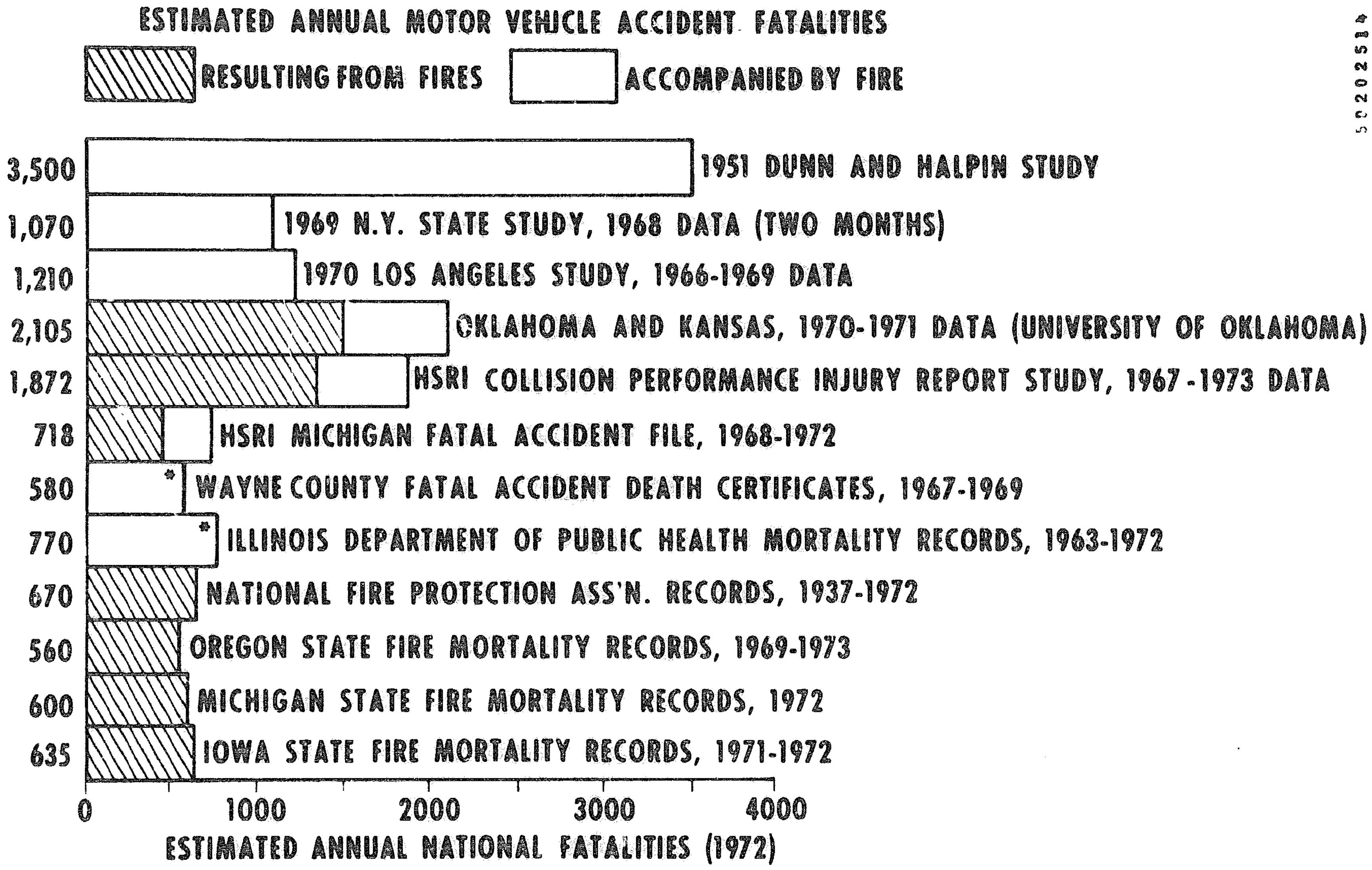
1. Cooley, Peter, Fire in Motor Vehicle Accidents, Highway Safety Research Institute, University of Michigan, April 1974, Report No. UM-HSRI-SA-74-3.



FROM HSRI SPECIAL REPORT, FIRE IN MOTOR VEHICLES ACCIDENTS, APRIL 1974

*REPORT TEXT INDICATES THESE WERE FATALITIES RESULTING FROM FIRES

Figure 2-1. A Comparison of Statistical Data.

surveys listed in Figure 2-1 were based on accident files and mortality records. These seven studies led to estimated projections of 450 to 760 fatalities in 1972 as a direct result of vehicle crash fires. These projections were based on the 0.98 percent to 1.7 percent of vehicle fatalities (excluding pedestrians and bicycles) due to fires found during these surveys. In addition, the National Safety Council (Reference 2) estimated that 1.5 to 1.75 percent of vehicle fatalities during 1973 were a direct result of fire. The average of all these percentages is 1.40 percent of motor vehicle fatalities (excluding pedestrians and bicycles), leading to a national projection of 625 fatalities resulting directly from vehicle fires during 1972. Since the data base used for these studies was drawn largely from reports and statistics which were not specifically designed to report vehicle crash fires, it is quite probable that the number of fire fatalities that actually occurred is considerably higher than this figure. However, in the absence of more definitive data, 625 was used as the minimum number of fire fatalities during this program.

The study done by the University of Oklahoma (Reference 3) using Oklahoma and Kansas accident data was specifically structured to study the motor vehicle crash fire problem. As such, the data should be complete and accurate in regard to motor vehicle fire deaths. Projections based on the Oklahoma and Kansas data regarding the percent of vehicle fatalities directly caused by burns leads to 1430 vehicle burn fatalities nationwide during 1972. However, the sample size was quite small. In addition, the data are biased towards more severe accidents, and thus more fire accidents, because of the predominantly rural location. Thus, this projected number of motor vehicle burn fatalities should be considered as near the upper limit until more definitive data are available.

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2. Accident Facts, National Safety Council, Chicago, Illinois, 1974 Edition.
3. Sliepcevich, C. M., et al., Escapeworthiness of Vehicles for Occupancy Survivals and Crashes, University of Oklahoma Research Institute, Report No. DOT/HS-800 736, July 1972, First Part.

The HSRI Collision Performance Injury Study shown in Figure 2-1 also resulted in a significantly higher number of burn fatalities than did the bottom seven accident and mortality record studies listed in Figure 2-1. Not enough information was available in the Michigan report, however, to determine possible reasons for the higher number.

National projections of motor vehicle burn fatalities during future years, based on the studies previously discussed, are presented in Figure 2-2. (The method of obtaining these projections is discussed in Section 5.6.1 in conjunction with the cost/benefit analyses.) Based on the minimum estimate of 1.4 percent of motor vehicle fatalities being a direct result of burns, this projection indicates that 14,000 people will die from motor vehicle burn injuries during the next 20 years. The number could possibly be as high as 30,000 if the higher burn fatality estimates are correct.

The above figures are for fatalities resulting directly from the fire and not from other collision-caused trauma. Although the total number of fatalities which occur in fire accidents is considerably higher than the figures quoted above, many of these fatalities would have occurred even if the fire had not been present. The Michigan study (Reference 1) estimated that from 720 to 1250 fatalities occurred in accidents accompanied by fire during 1972. However, estimates based on the Oklahoma and Kansas data would put the number of such fatalities at 2145. Again, the discrepancy is broad and the statistics limited. It should be emphasized that the 14,000 to 30,000 estimated burn fatalities in the next 20 years are victims who would have survived if a fire had not occurred.

Statistics on burn injuries are almost nonexistent. The only two studies which reported burn injuries along with fire accident fatalities were the New York report (Reference 4) and a

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4. Moore, J. O., and Negri, D. B., Fire in Automobile Accidents, New York State Department of Motor Vehicles, Research Report 1969-2, September 1969.

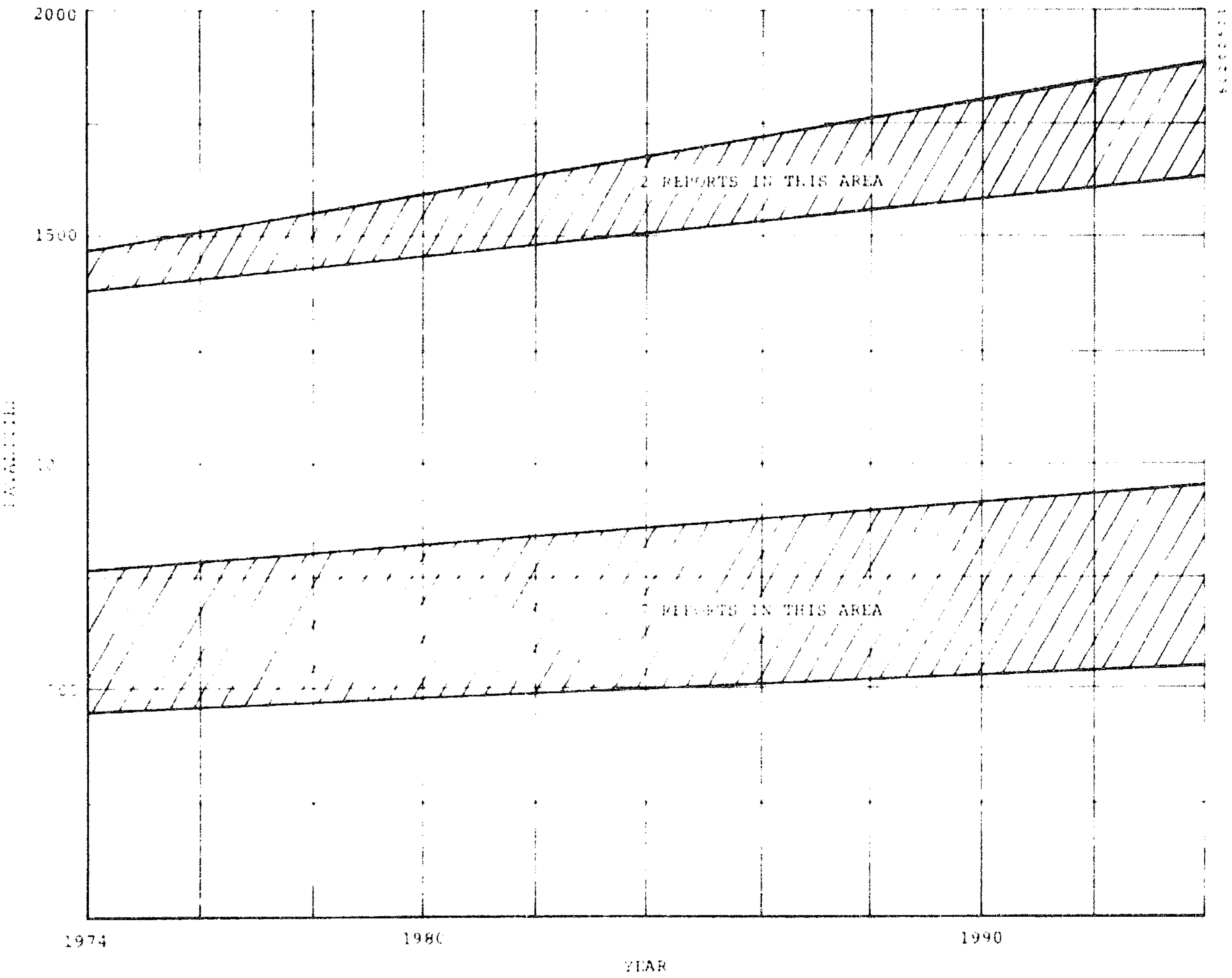

Figure 2-2. National Motor Vehicle Fire Fatality Projections (Based on Reference 1 and Figure 5-7).

Cornell report (Reference 5). Both of these studies were based on very limited sample sizes. The New York study reported 45 fire accidents out of a two-month total of 65,000 accidents in the state. Twelve of those injured received burns. The Cornell study involved 156 passenger cars involved in fire accidents out of a total 33,250 cars involved in injury or fatality producing accidents. Twenty-three occupants received nonfatal burns. In view of the millions of injuries each year in motor vehicle accidents, it would be extremely unreliable to forecast nationwide burn injuries based on such a small sample size.

Extrapolating the available fire statistics to a nationwide estimate of total motor vehicle crash fires per year magnifies the uncertainty of the statistics. This is obvious when considering that a difference of only 0.01 percent of the 1972 total of 17,000,000 accidents results in a difference of 1,700 accidents. Thus, again, the total number of fire accidents per year can only be estimated within a broad range. The average percentage of fires occurring in all motor vehicle accidents from New York, Kansas, and North Carolina data (from Reference 1) was 0.06 percent. (Individual percentages were 0.06, 0.07, and 0.04, respectively.) National projections for 1972, based on 0.06 percent, indicate that there were approximately 10,000 motor vehicle crash fires during the year. However, the North Carolina statistics alone project to only 6,800 fire accidents. Some explanation for this discrepancy may be found in the Cornell report (Reference 5) which shows that the percentage of fire accidents drops markedly as the accident severity decreases. Close examination of the New York and Kansas data show that the data bases used in these studies contained from 2.5 to 4.0 times the national average of fatal accidents in relation to all accidents. Thus, the data are biased towards more severe, and thus more fire, accidents. However, the

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5. Robinson, S. J., <u>Observations on Fire in Automobile Accidents</u> (Cornell Aeronautical Lab. Inc. of Cornell University, Buffalo, New York) CAL Report No. VJ-1823-R14, February 1965.

North Carolina data could be somewhat low since no separate space is provided on the accident report forms for noting the occurrence of post-crash fires.

In an effort to arrive at a minimum number of vehicle fire accidents and decrease the uncertainty of the national projections, statistics relating to only injury producing and fatal accidents were examined. The Cornell study reported that 0.45 percent of the vehicles examined showed fire damage. All of these vehicles contained at least one injury or fatality. Assuming that each burned vehicle was involved in a separate accident, this percentage leads to a national projection of a minimum of 5,800 crash fire accidents in 1972. The Oklahoma data showed that 34 percent of the fire accidents were fatal accidents. This leads to a national projection of 1,587 fatal fire accidents and 4,668 total fire accidents in 1972. Thus, the minimum number of vehicle crash fires per year is approximately 5,000 and could well be as high as 10,000 per year.

The statistics were also examined to determine the type of accidents that are likely to result in vehicle fires. This information was vital in determining vehicle modifications which were most beneficial in decreasing the number of vehicle crash fires. Although many reports were examined, none were consistent in their method of classifying accident impact vectors. The study done by the University of Oklahoma (Reference 3) best describes the types of impacts that have resulted in vehicle fires. Figure 2-3 (from the Oklahoma report) shows the five general types of accidents resulting in post-crash fires and the percentage each contributed to the total number of fire accidents. It is interesting to note that, in spite of the fact that gasoline is more readily available in rear end collisions, this type of accident shows the lowest percentage of fires. This directly reflects the lower incidence of moderate to severe rear end collisions as compared to the other types of impacts.

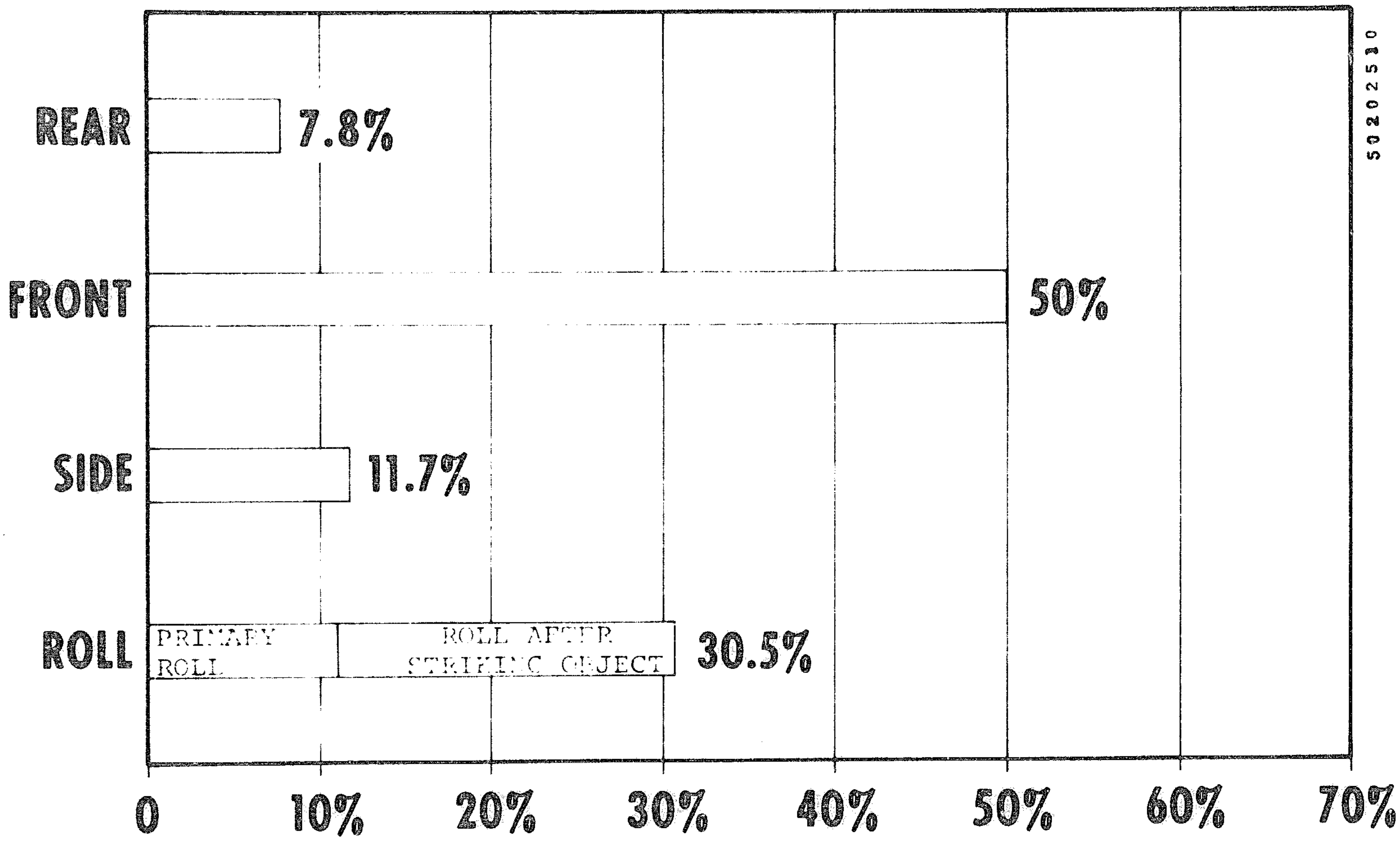

Figure 2-3. Percent of Impact Areas Involved in Post-crash Fire Accidents.

The time of day fire accidents occur was also examined for possible clues to ignition sources. The National Safety Council (Reference 2) indicates that 31.8 percent of all accidents occur between 7:00 PM and 7:00 AM and 49 percent of the fatal accidents occur in this time period. However, three reports (Reference 3, 4, and 6) all indicate a larger percentage of accidents with fire at night than in the daytime. These percentages range from 55 to 74 percent. The higher number of nighttime fire accidents cannot be attributed entirely to the larger number of serious accidents at night since only 49 percent of all fatal accidents occur then. Other factors which might cause this increase in vehicle fires at night are an increased vehicle electrical load and broken headlights serving as ignition sources. A detailed analysis of these two factors is presented in Section 3.4 of this report.

2.1.2 Fuel Leakage by Accident Type and Severity

Two items are required in a vehicle for a fire to occur: first, a source of ignition and second, something that will burn. In the majority of post-crash fires, gasoline will be the substance that will initially burn. The specific characteristics of gasoline are discussed in Section 3.4. This section describes the type of accident conditions under which gasoline is available for combustion. Figure 2-4 indicates leakage of gasoline based on the type of accident and the severity. This information is from the Michigan report on vehicle fire accidents (Reference 1). Fortunately for the driving public, the rear area of the vehicle, which shows the highest percentage of fuel leakage, does not have an ignition source as readily available as does the front end which contains the high voltage electrical components and the battery.

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6. Vaughn, Rodney G., Fire in Road Accidents, Traffic Accident Research Unit, Department of Motor Transport, New South Wales, January 1970.

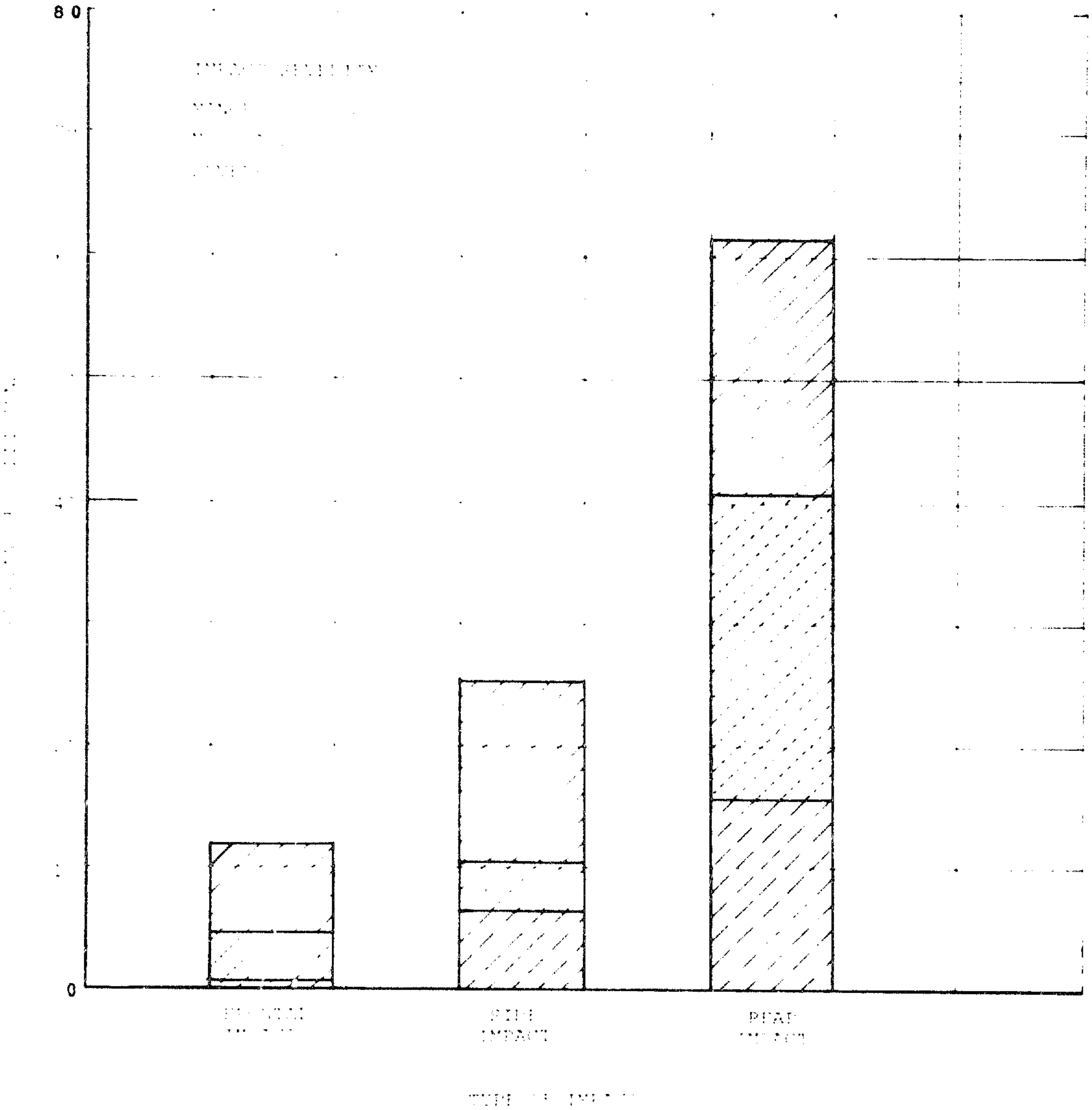

Figure 2-4. Percentage of Fuel Leaks in Accident.

2.2 EXISTING FUEL SYSTEMS

2.2.1 Fuel Tank Locations

Fuel tanks have at one time or another been located in almost all possible locations in an automobile. In the past, fuel tanks were located on the firewall above the engine, under the driver's seat, and with the engine, but these locations have disappeared over the years. In today's vehicles the engine and fuel tank are generally placed in opposite ends of the car. In a large percentage of American passenger vehicles, the fuel tank is mounted under the trunk floor between the rear bumper and the differential housing. The tank is strapped in with two steel bands. Tanks on station wagons may be located in the rear side panels of the vehicle or suspended under the rear of the vehicle. These tanks are also strapped in with two steel bands. Vehicles manufactured outside the United States may have fuel tanks in other locations. In the Volkswagen Beetle, with a rear-mounted engine, for example, the tank is located under the front hood, while the Fiat 850 has a rear-mounted engine with the fuel tank located over the aft part of the engine. Light trucks (pickup) generally have the main fuel tank mounted behind the seating area in the cab.

Tank filler locations are also an important aspect of fuel system structural integrity. Fillers may be either hard mounted to the tank or connected from the tank to the vehicle body with a flexible connector. In vehicles with rear-mounted fuel tanks, the fillers are located in either rear side panels or in the bumper area. A few vehicles have the filler located on the rear trunk deck. Pickup trucks are generally filled from the driver's side of the cab. Each location provides advantages and disadvantages in certain types of impacts. Vehicles with front-mounted tanks likewise have their fillers mounted in close proximity to the fuel tank in either front side area. For a complete description of tank locations and filler types, see References 7 and 8.

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7. Fuel Tank Protection, An Investigation of Fuel, Exhaust and Electrical Systems as Related to Post-Crash Fire Safety, Volume I, (Fairchild Hiller, Farmingdale, New York) under Department of Transportation Contract No. FH-11-6919, 30 June 1969.
8. Johnson, N. B., An Assessment of Automotive Fuel System Fire Hazards, (Dynamic Science, Phoenix, Arizona) for Department of Transportation under Contract No. FH-11-7579, December 1971.

2.2.2 Fuel Lines

In general, American fuel lines are 5/16-inch welded steel tubing running from the vehicle fuel tank to the engine fuel pump. Fuel lines are flexibly mounted to the tank through a short piece of rubber tubing. Carburetor lines and lines into the fuel pump may be solid or a combination of solid and flexible rubber lines. Lines from the fuel pump may run directly up the side of the engine block to the carburetor or cross over to the carburetor on the front of the engine. Some foreign vehicles, such as early model Volvos, used a steel mesh over rubber lines in the engine compartment. These lines used solid-type screw-on fittings rather than compression-type hose clamps. See Reference 7 for specific vehicle configurations.

2.2.3 Fuel Pumps

The majority of vehicles in this country use engine-mounted, cam-actuated fuel pumps. These pumps normally are located low and toward the front end of the engine. Due to their compact design and mounting position on the engine block, they are not normally subject to damage. Some production vehicles now are equipped with tank-mounted electric fuel pumps, and thus gasoline is under pressure in the fuel lines from the vehicle fuel tank to the carburetor rather than just from the engine block to the carburetor. Some of these pumps are installed in such a manner that, if the engine is not running, the pump will not operate. (The Vega pump senses off of engine oil pressure and stops running when the oil pressure drops below a specified level.) Other units will continue to run until electric power is removed by turning off either the ignition switch or a separate fuel pump switch. Some fuel pumps vent excess gasoline back to the fuel tank. Lines for the pump vent are mounted and routed in a manner similar to the main fuel line.

2.2.4 Evaporative Control System (ECS)

Prior to 1971 (1970 in California) the vehicle fuel tank was vented overboard, but since 1971 fuel vapor emissions have been controlled in a closed fuel system and vehicles now vent tanks into some sort of liquid-vapor separator. There are as many different methods to meet the vapor emission requirement as there are auto manufacturers, but, in general, the type of operation of all these systems is the same.

American Motors uses a float-type check valve in the vent line to prevent any liquid from leaving the tank. Chrysler uses a system of standpipes and vents the tank from four corners, and Ford uses a small unit mounted right on top of the tank. The vapors from the liquid-vapor separator are stored while the vehicle is not in operation.

There are three basic methods of storing the fuel vapors: in a carbon canister, in a storage tank, and in the engine crankcase. The most common systems in the U.S. use the carbon canister or the crankcase for vapor storage. In either case, vapors are stored in a holding area until the engine is started and the vapors are drawn into it to be burned. The carbon canister uses activated charcoal to adsorb the vapors, and when the engine is running, fresh air flows through the canister and the vapors are routed to the engine.

Vehicles that use the closed systems use a pressure-vacuum relief cap on the tank filler. This cap is designed to relieve pressures of 0.50 to 1.25 psi and vacuums of 0.25 to 0.50 psi.

This closed system can prevent large amounts of fuel spillage from the vent line in a rollover crash, but it does increase the number of fuel-associated lines in the vehicle. Also, fuel can leak out the filler cap, depending on the vehicle orientation after a rollover and the amount of fuel in the tank, since the head pressure on the filler can be over 0.50 psi. For a complete analysis of ECS components and their locations, see Reference 8.

2.2.5 Carburetors

With the exception of fuel injection systems, the fuel distributing devices (carburetors) are all subject to the same fuel leakage problems due to a primary or secondary rollover. The vehicle carburetor draws fuel off one or two float bowls. These float bowls are vented to the atmosphere, normally into the airhorn. When the vehicle is rolled over, the contents of the float bowl or bowls will drain out within about ten seconds. Carburetors may spill from 30 ml in single-barrel small units to 200 ml in dual four-barrel units.

The carburetor is located on 8-cylinder engines in the middle of the engine, on top, in a relatively well protected area. Carburetors on 4- and 6-cylinder front engine cars are also relatively well protected in an impact due to the manifold structure on which they are mounted. Carburetors on rear engine cars, such as the Volkswagen, are in a location which is more likely to be damaged than in American vehicles. The location of the carburetor on the rear area of the engine leaves it in a position susceptible to rear end impacts.

2.3 EXISTING ELECTRICAL SYSTEMS

2.3.1 Battery Location and Connection

The battery has been located in as many locations as the vehicle fuel tank, but, in general, it is located in the vicinity of the engine. A battery which is located any significant distance from the starting motor and other heavy current accessories will require large cables to minimize voltage drop. The Fiat 126 locates its battery in front with a rear engine, but this car is very short and thus does not have long cable runs.

A large percentage of batteries are mounted in the front area of the engine compartment and are not well protected in front end collisions. Those mounted further back in the engine compartment are better protected by the engine. In some foreign vehicles, the battery has been mounted over the engine on the firewall. The location in some earlier model Jaguars was behind the wheels in the front wheel wells. In this case, two 6-volt batteries were connected to obtain a 12-volt circuit. In some rear engine cars, notably the Volkswagen Beetle, the battery is mounted under the back seat, although the Fiat 126 battery is under the hood in front.

Most batteries have either top-mounted contact posts or side-type terminals. In most cases these terminals are bare metal. Certain foreign cars coming into the country have a plastic boot that is slipped up over the terminals and protects them from accidental shorts.

Battery cables are heavy copper cable, normally around 6 gage, and are well insulated. However, terminals are exposed and can be shorted out easily, the exception being those few vehicles which have plastic covers which pull up over the terminals.

2.3.2 Vehicle Wiring

All vehicles have a large amount of current-carrying wires. These wires vary in size from 6 gage at the starter to 18 gage for low current application, with varying sizes in between. As the size of the wire increases, the potential hazard it represents also increases since it will be carrying more current.

Wiring will be routed in various patterns in vehicles. Much of the wiring is protected by the vehicle structure. However, some wiring, such as horn, headlights, or taillights, is in a position to be torn away in an impact.

In newer model cars all wiring is well protected with insulation and firmly attached to the items it powers; however, in an impact the wiring may easily be torn or ripped loose from its mounting lugs. Even if the wires are well protected, the components they connect to may not have insulated terminals, and thus deforming of sheet metal can cause short circuits. For further information on wire routing, see Reference 9.

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9. Gatlin, C. I., and Johnson, N. B., Prevention of Electrical System Ignition of Automotive Crash Fire, (Dynamic Science, Phoenix, Arizona) for Department of Transportation, NHTSA under Contract No. DOT-HS-800-392, March 1970.

2.3.3 Vehicle Lights

Automotive headlights in a front impact will most likely be struck and some broken although they do not tend to break easily. It is well known that broken aircraft landing lights have been responsible for fires. However, the literature survey did not indicate anything other than speculation in regard to the fire hazard associated with headlights.

Taillights also fall into this category, but their wattage is many times lower than that of the headlights. They are extremely prone to damage from rear end impacts.

2.3.4 High-Energy Electrical Components

Vehicle starters, solenoids, and their associated wiring carry very high current levels. However, starter and solenoid combinations are generally well protected during a crash because of their location in a low area on the engine and their very rugged construction. When a remote solenoid is used, it is located in the vicinity of the battery and is susceptible to shorts due to its exposed terminals.

Vehicle alternators or generators and their associated wiring carry loads up to 55 amperes at 12-14 volts. They are located on the engine in a forward position since they are driven by V-belts from engine drives. Although they are sturdy devices and a considerable amount of crush must take place in order to reach them, they do have exposed terminals in some cases which could be shorted.

Voltage regulators are located in a random pattern in the engine compartment. Although they do not damage easily, some do have exposed terminals which can be shorted. In many cars, the voltage regulator is located on the firewall or the splash guard adjacent to the radiator. It is least vulnerable in the firewall location and most vulnerable on the splash guard. Voltage regulators on rear engine vehicles have locations similar to front engine vehicles.

The coil and distributor on V-8 engines are mounted either in front of or behind the carburetor. Either place is well protected since both are on top of the engine. On 4- or 6-cylinder engines these components are usually located midway back on the side of the engine and are therefore more vulnerable to damage than those on the V-8's. Even if this system is damaged, heavily insulated plug wire must be severed or pulled loose before a spark will occur.

Some late model vehicles are equipped with electronic ignition systems. These systems do not eliminate the coil or distributor, but do remove the breaker points and the condenser requirement. A sensor within the distributor operates at low voltage and signals a solid-state circuit to open or close the coil primary. Thus a potential ignition source has been removed.

For a complete description of electrical system components in regard to location, refer to Reference 9.

2.4 AVAILABLE FUEL SYSTEM COUNTERMEASURES

2.4.1 Safety Fuel Tanks

Safety fuel tanks have been manufactured for many years, both in this country and abroad. Aircraft needs produced the first tanks of this type, and the technology spread to the auto racing industry. Auto racing has shown the need to contain fuel in high-speed impacts, and the information gained in this area can prove to be beneficial to the driver of a passenger car. Table 2-1 shows the minimum requirements set down by various racing organizations for vehicles which run in their sanctioned events.

Table 2-2 lists the companies who manufacture safety fuel tanks. Most manufacturers which were contacted used a cloth-type material which was coated with rubber elastomer. Two manufacturers used ballistic nylon which was coated with urethane, and one manufacturer used a thermoplastic material. Five additional manufacturers responded to inquiries but their data were inadequate to make any evaluations.

TABLE 2-1. FUEL TANK SPECIFICATIONS

Organization	Tensile Strength (lb)	Tear Strength (lb)	Puncture Test (lb)
SCCA	450	50	175
NASCAR	450	50	175
USAC	450	50	175
USAC (proposed spec)	600	150	250

TABLE 2-2. SAFETY FUEL TANKS

Manufacturer	Identification Number	Need For Container	Cost (1)	Additional Data
Aero Tec Lab	421-D	Pillow	-	
	426-C	Yes	-	
	PC-116	No	$75.00	
Lon Allen	-	Yes	-	
Firestone	-	-	-	Data Not Made Available
Fuel Safe	-	Partial	$50.00	
FPT	FPT/RS/669	Yes	-	
Gene White	-	-	-	Insufficient Information
Goodyear	DX-344	Yes	-	No Strength Data Available
	BTC-60-5	Yes	-	
	BTC-60-9	Yes	-	
	BTC-60-10	Yes	-	
Kleber Colombes	-	Yes	-	
McCreary	Hytrel	Yes	-	
Simpson	-	Pillow	-	
Sumitomo	SCP	Yes	-	
Uniroyal	D-755	Yes	$60.00	

(1) Estimated Mass Production Costs

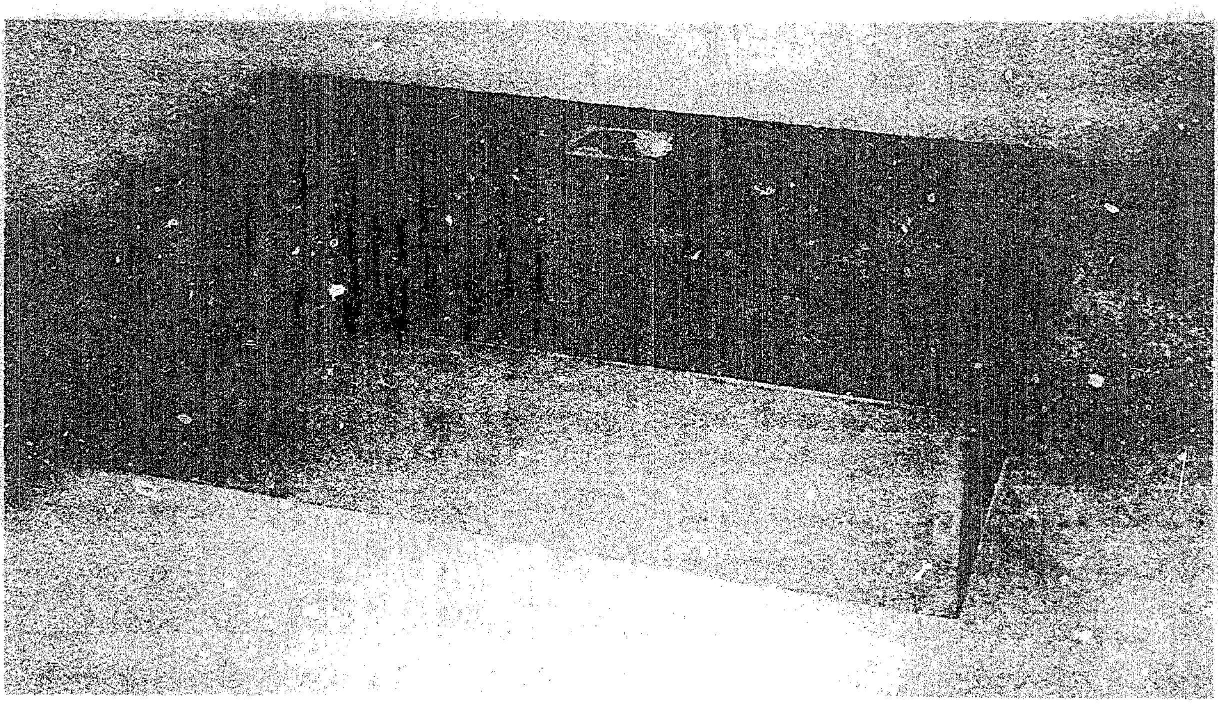
All materials meet or exceed present safety requirements except as noted.

Fuel tanks were available in three main configurations: a freestanding bladder, a bladder that required containment, and pillow tanks. The pillow tanks are used as add-on items in cars, trucks, or boats and are not meant for permanent installation. They are basically used for additional fuel capacity and are removed, folded up, and stowed when not in use. To operate this type of tank, a line is inserted in the filler of the existing tank and the pillow is pressed; fuel starts flowing into the main tank and stops when the shuttoff on the pillow tank is turned off. This type of tank would have no application as it is configured in a production automobile; however, it does provide a safe method to carry additional fuel.

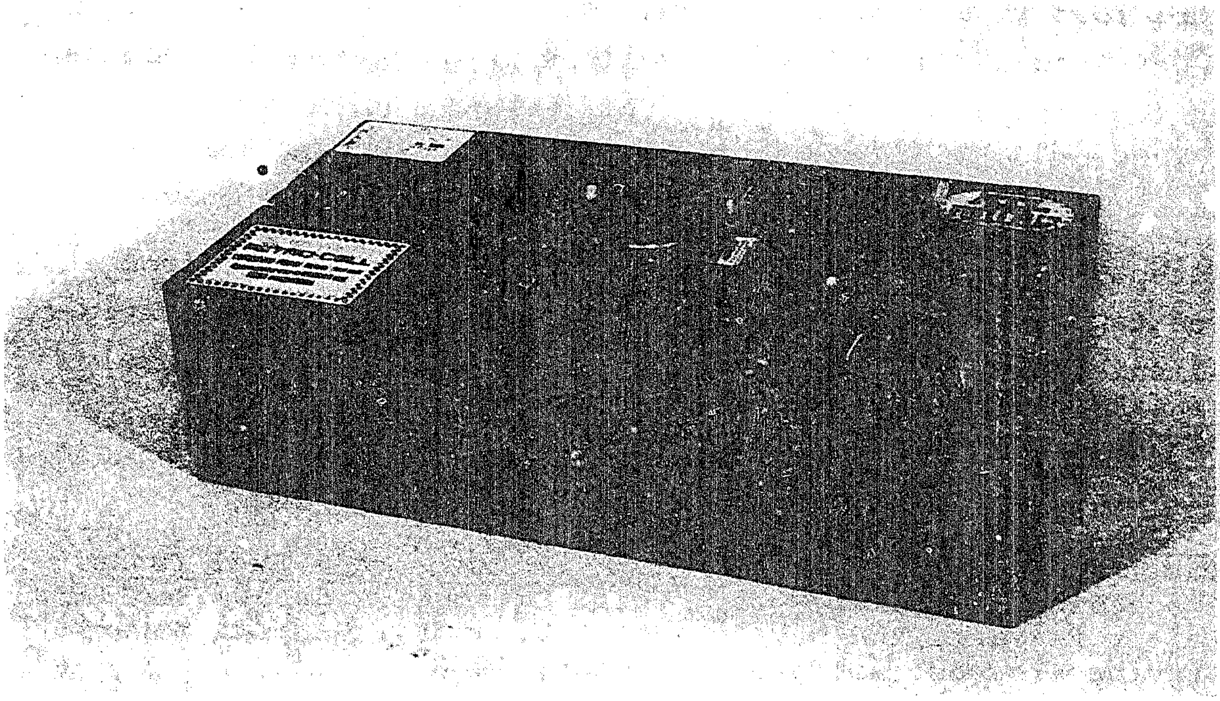
Bladder tanks, in most cases, require some kind of containment to retain their shape and properly refill. Tanks in this category have been made from a fabric covered with urethane or some other elastomer. These types of tanks would readily lend themselves to production design due to the variety of shapes into which they can be formed. This is especially true of the urethane-coated tanks. The metal containers which are used with these tanks are a very light gage steel or aluminum. In production vehicles this could be part of the vehicle structure.

The freestanding bladder tanks are able to maintain their shape due to the heavier gage material used in the construction. Two freestanding bladder tanks were investigated; one was made from ballistic nylon material with a thick coat of urethane, and the second was a tank of thermoplastic material. The urethane-coated ballistic nylon tank is freestanding only when it is filled with reticulated foam and placed in a 2-inch-deep container. The tank is then strapped in place. The thermoplastic tank is totally freestanding and requires only two straps to mount just as do present production fuel tanks.

Figure 2-5 shows two production configuration safety cells. The one in the metal case (Figure 2-5a) is ballistic nylon coated with urethane. The case provides a supporting structure in this



a. Ballistic Nylon Tank With Aluminum Case.



b. Thermoplastic Freestanding Fuel Tank.

Figure 2-5. Production Configuration Safety Fuel Tanks.

application. The other tank (Figure 2-5b) is a thermoplastic material and is freestanding.

The majority of the tanks investigated were sold filled with reticulated foam. Claims from manufacturers included slosh reduction, prevention of explosion, and reduction of fuel spillage if the tank is ruptured. The first two aspects attributed to foam are quite true. It provides an excellent slosh barrier and is used in many race cars and boats for this purpose. It also has been tested extensively by the military to determine its ability to prevent explosions and does function in this area as an excellent flame arrestor. Tanks filled with foam have been shot with incendiary rounds and do not explode; however, the same tank will explode without the foam protection.

The claim to reduce fuel spillage, however, does not seem warranted. A Study of Automobile Fuel Tanks (Reference 10) shows that the reduction in leakage is not significant. Testing was done on containers without foam and on those containing foam with 10 pores per inch (ppi). With a 2-5/8-inch-diameter hole, 4 gallons were lost in 6 seconds without foam and 4 seconds with foam. With a 3/4-inch-diameter hole, 4 gallons were lost in 58 seconds without foam and 50 seconds with foam. The final test was with a slit 2.00 by 0.020 inches. In this case, 4 gallons were spilled in 11 minutes without foam and 12 minutes with foam.

Although flow is not decreased to any extent, spray from a ruptured tank is. A test program was done for the Federal Aviation Administration by Firestone (Reference 11). Approximately

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10. Ridenour, J. B., et al., A Study of Automobile Fuel Tanks, Proceedings, General Motors Corp. Automotive Safety Seminar, Safety Research and Development Laboratory, General Motors Proving Grounds, Milford, Michigan, 1968.
11. Yancy, M. M. and Headrick, R. T., An Engineering Investigation and Analysis of Crash-Fire Resistant Fuel Tanks, (Firestone Coated Fabrics Co., Akron, Ohio) for FAA on Contract No. FA-67 NF-245, July 1970.

30 psi flow was forced upward through a 1-inch-square orifice and the flow height was determined. Flow was instituted by rupturing a diaphragm. Pressure was not maintained, thus simulating the situation encountered in a fuel tank rupture. With no foam, flow reached 40 feet, with 10 ppi foam only 9-13 feet, and with 40 ppi foam, flow was reduced to 3-6 feet.

2.4.2 Fuel Tank Hardware

Tank filler plates for the safety fuel cells are oval in shape and are attached to the tank with up to 24 1/4-inch bolts. The bolt ring is an integral part of the tank and is tapped to accept the cover plate bolts.

Cover plates are available in a variety of fitting configurations and would adapt well to production vehicles with the exception of cost. Today's plates are set up for racing and generally include a 2-1/4-inch or larger filler, fuel outlet, vent line, and two return lines. These attachment fittings are AN hardware but could just as easily be standard hose fittings. In general these covers are adapted for a cylindrical fuel level gage if one is used. This is due to the problems encountered with a swing arm gage if the tank is foam filled, as many are.

Fillers are available with built-in check valves to prevent fuel spillage in a rollover crash. These valves may be either a flapper valve or a flat rubber plate check valve. Positive acting ball-type check valves are also available in the vent outlet on the cover plate. This is of great importance in the present application of these tanks since they are normally vented to the atmosphere instead of through an evaporative control system.

Figure 2-6 shows a typical filler cover plate with two return lines, a vent, a filler, an outlet, and a mounted swing arm gage.

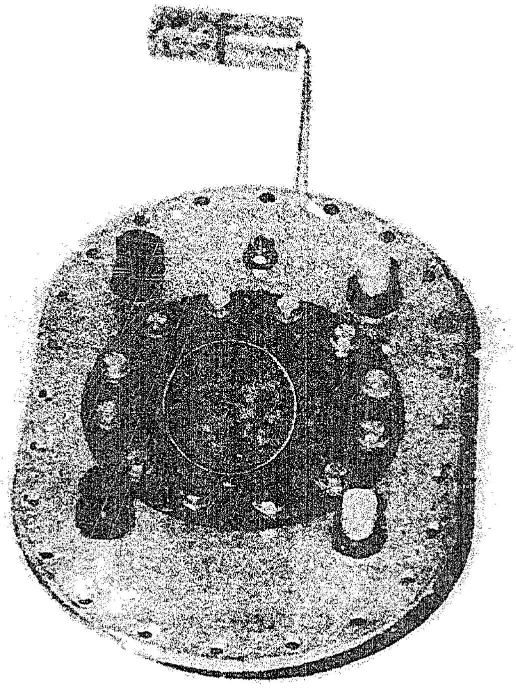

Figure 2-6. Typical Filler Cover Plate for Safety Fuel Tank.

2.4.3 Breakaway Valves

These items have been incorporated in a number of military aircraft fuel systems but have not found wide application in automobiles. They are used to a limited extent in automobile racing but are very expensive. Only one company was found that provided breakaway valves specifically for automobiles. Another company had manufactured a few items for a special race application but no production items.

These valves are designed to separate under loads which are less than the loads that would be required for line failures. The valves shut off each end of the fuel line on separation. They are mounted where a line may be stretched due to impact such as at a bulkhead. Figure 2-7 shows a breakaway valve.

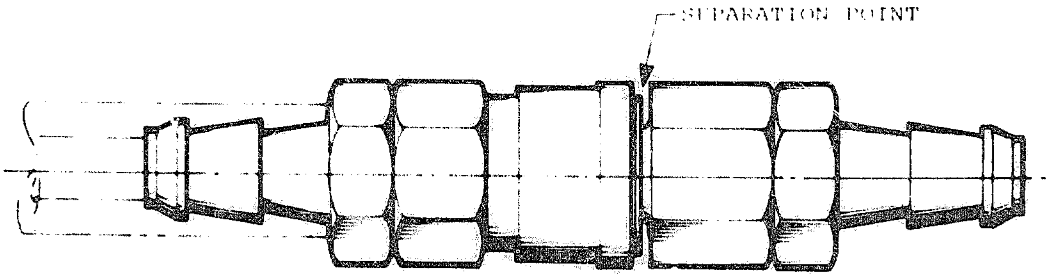

Figure 2-7. Typical Breakway Valve.

2.4.4 Inertia Fuel Shutoff Valves

Inertia fuel shutoff valves are placed in the fuel line between the vehicle fuel tank and the carburetor and are triggered by impact forces. These valves are set to function in the range of 5 to 10G acceleration. The units are to be installed in the line between the fuel tank and the fuel pump (with mechanical pump) or fuel pump (electrical) and carburetor. In case of a line break in the engine compartment, fuel would be shut off and could not feed a fire.

Valves were obtained from two manufacturers. One valve was omnidirectional and the other was sensitive in a longitudinal and vertical direction; however, the manufacturer can also make the device sensitive in a lateral direction.

In addition to inertia fuel shutoff valves one company contacted had made a rollover fuel shutoff valve. This valve would shut off fuel flow to the carburetor when the vehicle was rotated more than 60 degrees; thus even when a car came to rest on its side, fuel flow would be totally shut off. This same valve may have application in prevention of spillage from carburetor float bowls.

2.4.5 Fuel Lines and Fittings

Improved items in this area are readily available. AN-type attachment hardware is available and has been used on all types of aircraft systems. These fittings provide a positive pressure-tight seal. In addition to fittings, a steel braid-over-rubber fuel line is available. This type line provides flexibility in areas where movement of lines is important, and it provides greater strength and protection than can be afforded by conventional rubber lines. These lines are used extensively in aircraft application where the features these lines offer can be put to best use. These lines and hardware are more expensive than present equipment that is used on automobiles.

2.5 AVAILABLE ELECTRICAL SYSTEM COUNTERMEASURES

2.5.1 Inertia Shutoff Switches

Three different types of inertia-type electrical shutoff switches are available from three different manufacturers. One switch, shown in Figure 2-8, uses a steel ball resting on a conical plastic seat and held in place by a magnet. This particular dynamic system integrates the deceleration with time and requires two quantities to be exceeded. A deceleration threshold must be met and a velocity change must occur. Figure 2-9 shows the operative characteristics of this type of switch. A preset "G" level must be reached before the steel ball is able to break loose from the magnetic restraint. When the ball does leave the seat, there is a reducing magnetic restraint as it moves upward along the cone walls to contact the switch mechanism. The shaded area of the curve indicates the velocity change which is required before the switch can function. The response level and angle can be easily changed by varying the cone angle and magnetic restraint levels. In a rollover condition restraint levels are somewhat lower since gravity is aiding rather than detracting from operation levels. Inertia Switch Ltd. of England manufactures switches of this type. Switches are available which switch 12 volts 10A on or off and 12 volts 160A on or off. Switches are also available which combine the high and low current function into one package. This type of switch not only guarantees that main vehicle power will be disconnected but also stops the alternator circuit, assuring the engine will stop running as well.

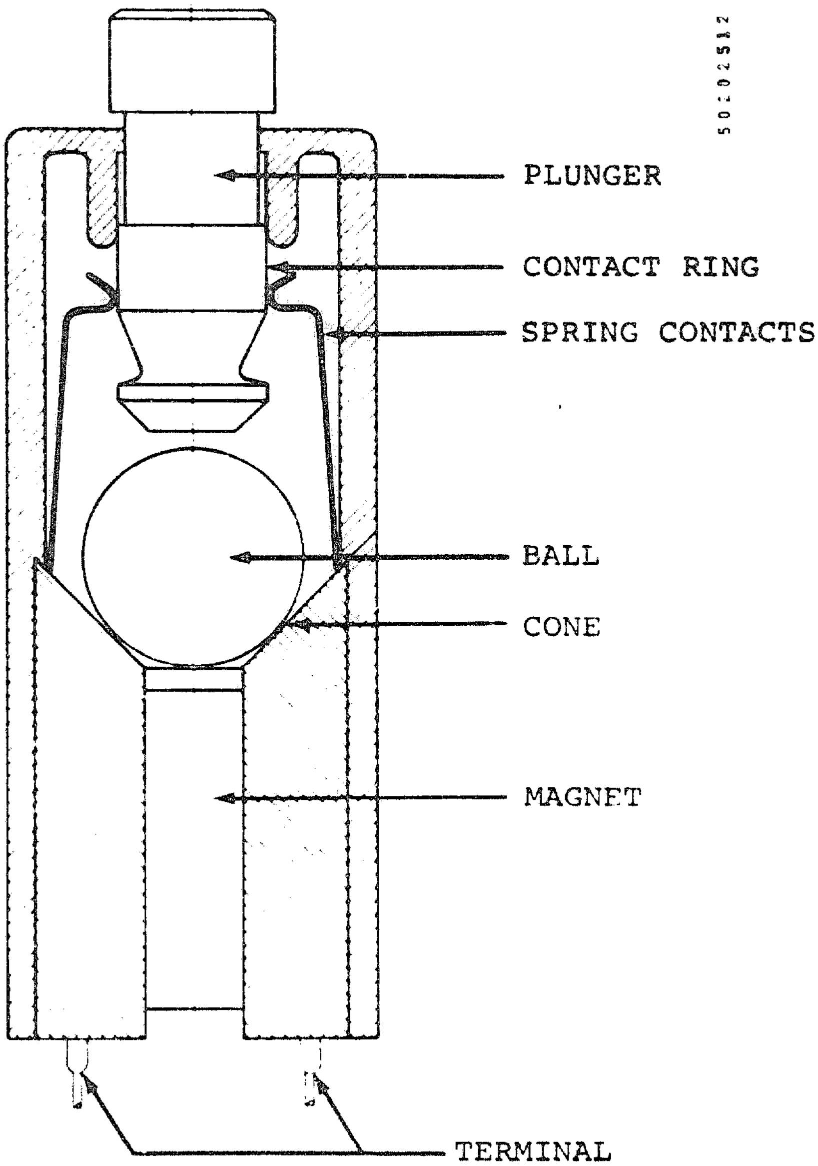

Figure 2-8. Inertia Switch Ltd. Electrical Shutoff Switch.

Figure 2-10 shows the switching system manufactured by A.C.B. Corporation. This switch also functions in an omnidirectional mode. Two sensors are used to accomplish this directional characteristic. In the horizontal mode a steel ball rests on a conical surface just as in the previous sensor; however, it is not held in place by a magnetic force but only by gravity. When acceleration begins, the ball moves up the incline and presses against the spring-loaded metal plate, which, after a specified

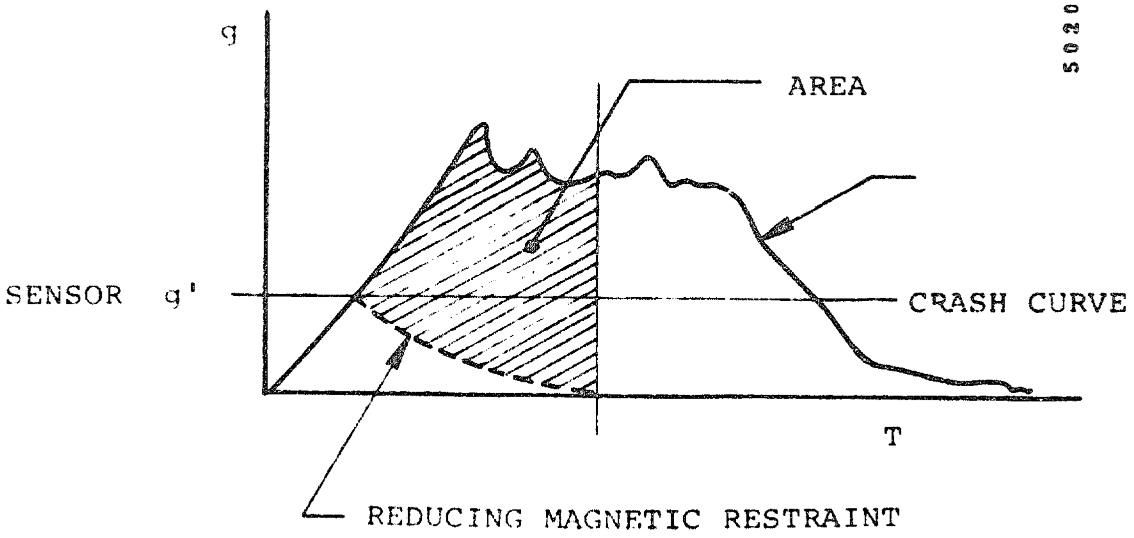

Figure 2-9. Operating Characteristics of Inertia Switch Ltd. Electrical Switch.

deflection, completes the circuit to the solenoid. The solenoid actuates a lever arm which removes the battery's negative terminal from ground. This switch also uses a vertical sensor for rollover operation. Again a steel ball is used. When the vehicle rolls over, the ball is acted upon by gravity and makes contact between a metal plate and a metal housing. This then actuates the solenoid and disconnects the battery in the same fashion as when used in the horizontal mode. An auxiliary lead is also used in either the alternator or distributor lead to block current and effectively stop the engine which could still run even though the battery was disconnected. This particular switch offers another advantage since the vehicle's battery can be easily disconnected by pushing a button on the switch itself or a remotely located button in easy reach of the driver. This provides the additional advantage of being able to disconnect the battery during an electrical fire or to work on the car. The A.C.B. Corporation also has a smaller sensor of the same design as shown in Figure 2-10.

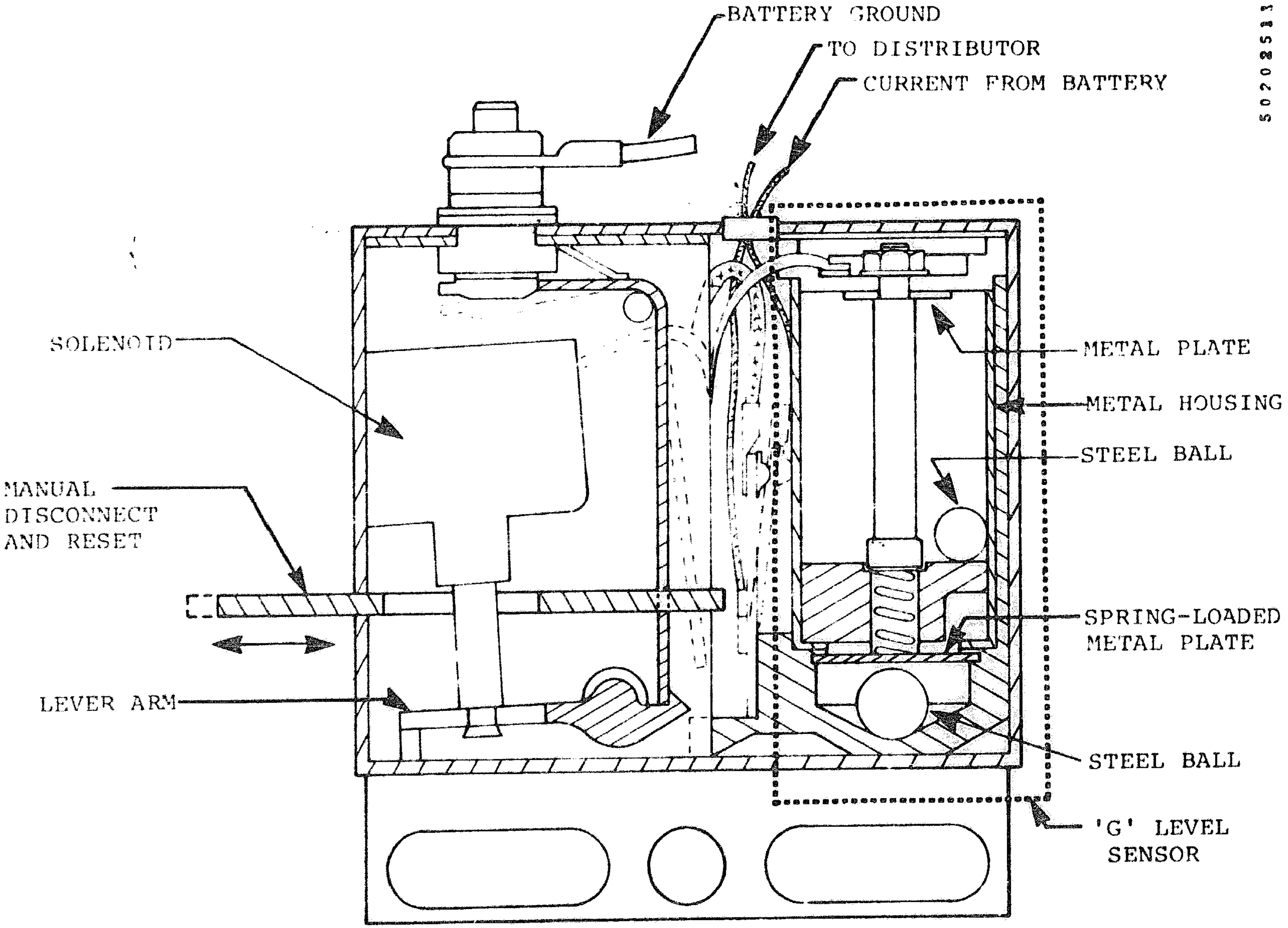

Figure 2-10. A.C.B. Corporation Electrical Shutoff Switch.

Figure 2-11 shows the inertia sensing system Technar Inc. employs in their inertia shutoff switch. The sensor or detector is a spring mass rolamite device. A band passes around two rollers, acts as a spring, and resists their motion. The spring can be shaped so the force on the rollers is an arbitrary function of roller location. This design has negligible friction and is only sensitive to forces in its axis (Reference 12). Due to this type of design, a switch mechanism using these sensors can be made more or less sensitive in certain impact directions. Within the switch package they employ 5 sensors, 4 in the horizontal axis and 1 in the vertical axis. The vertical axis switch is sensitive only to gravity and does not require an impact to operate; however, it does have a built-in delay of around 750 msec. This is accomplished through the use of fluid dampening in the sensor.

When a signal is sensed from one or more switches during an impact, it actuates a small relay through a capacitor to compensate for short delay times. This relay then closes and operates a larger relay which carries the load levels the switch has been designed for. This switch receives power from the ignition switch of the car and moves into a closed circuit when the ignition switch is turned on. After an impact the device turns off, and power must first be removed from the switch before it can be reset. This type of unit also offers the advantages of being able to disconnect the battery if an electrical fire should occur while driving. If the vehicle is parked and the ignition switch is turned off, vehicle power is also removed. The sample device received from Technar was designed to handle 50 amperes of vehicle power; however, a device which would handle starter power in addition would only require a larger secondary relay.

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12. Bell, Lon E., Crash Detector Development, Society of Automotive Engineers, Second International Conference on Passive Restraints, Detroit, Michigan, May 22-25, 1972. Report No. 720421.

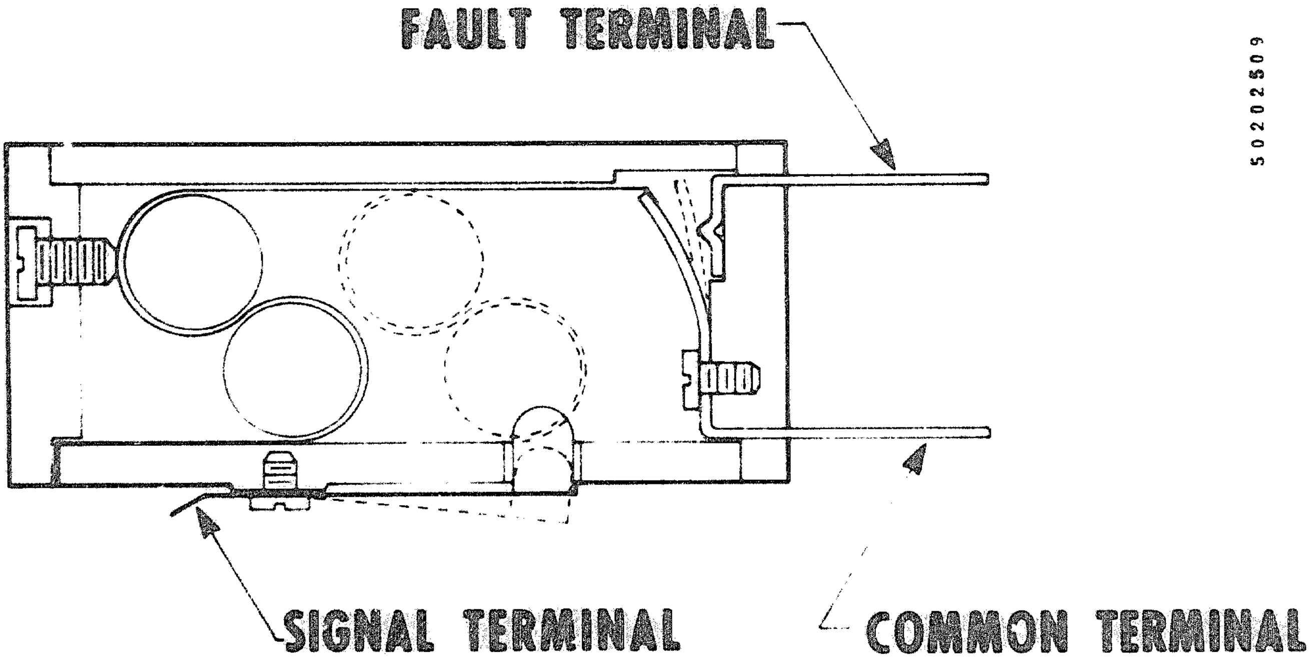

Figure 2-11. Technar, Inc. Electrical Shutoff Switch.

The devices investigated were specifically designed for automotive application; however, there are other companies which do produce inertia devices for other applications which could apply their skills to automotive applications.

2.5.2 Battery Terminal Protection

Certain vehicles today have battery terminal protection. Fiat uses a rubber cap which is pulled up over the battery terminal after it is connected. This device prevents inadvertent shorts to the positive battery terminal while working on the vehicle. Protection is also provided to a certain extent due to sheet metal deformation in a crash situation. A battery clamp which might show promise for automobiles was designed for marine applications. The manufacturer claims it is corrosion free. The clamp has a neoprene o-ring seal and antimonial lead connector cap with a set-screw which secures it to the cable. It comes with a plastic housing.

Although not many devices were found which provided battery terminal protection, they would not require a large amount of engineering and cost could be low; thus, they could easily be designed and produced if a requirement for them was found.

3.0 IGNITION SOURCE DEFINITION

3.1 GENERAL

For a fire to result, two items must be present, fuel and a source of ignition. It is a well recognized fact that gasoline is the fuel involved in most automotive post-crash fires, but a number of different opinions exist as to the methods of ignition.

Unfortunately in vehicle fires the ignition source is usually destroyed, thus no evidence exists of which possible source actually caused the fire. However, many newspaper articles, police reports, and witnesses state with firm conviction that a certain item was responsible for igniting the fuel. This leads to many misconceptions over what constitutes a dangerous ignition source.

To properly analyze a problem such as post-crash fire and make recommendations in regard to what can be done to reduce the incidence of such an occurrence, an accurate definition of the ignition source is necessary. It would do little good to remove an ignition source which causes only 5 percent of the fires and totally ignore those sources that are responsible for the remaining 95 percent. Therefore, the results of the literature survey were analyzed to determine the components of a vehicle which might be potential ignition sources and the relative degree of hazard associated with each source. The areas which were considered as possible ignition sources were tested under laboratory conditions to determine whether or not they actually posed a hazard. Along with this study of ignition sources, the flash point, autoignition characteristics, and combustible range of gasoline were obtained from the literature.

3.2 POTENTIAL VEHICLE IGNITION SOURCES

3.2.1 Broken Electrical Wiring

Electrical wires are found in almost every area of a vehicle where an impact may take place. These wires vary in size from 20 gage to 6 gage or larger. Wires present a hazard from two standpoints. First, if a circuit wire on the voltage side of a switch is broken, it can short and produce sparks by coming in contact with the vehicle ground whether the circuit is in operation or not. Second, the breaking of a current-carrying wire can produce a discharge spark (extra-current spark). The energy of this spark depends on whether the device the wire has been supplying is capacitive or inductive in nature and the size capacitor or inductor it represents. Any vehicle wiring in the 12-volt battery circuit or the high-tension ignition circuit must be considered a potential ignition source in either of the two sparking modes mentioned above.

3.2.2 Broken Headlights

Although little has been done to determine if automobile headlights are a possible ignition source, it is known that aircraft landing lights are a source of ignition in aircraft crashes. Automobile headlights as well as taillights can function as ignition sources in two ways. First, a hot surface is available for a certain length of time after the lamp is broken, and second, when the filament does break, a spark is formed. Headlights and taillights are vulnerable to damage due to their position on the vehicle. Any time the front of the vehicle is involved in an impact, from one to four headlights may be broken and provide a possible ignition source.

3.2.3 Displaced or Broken Battery

From outward appearance this could possibly be the most dangerous ignition source. Although the cables leading from the battery are well insulated, the battery terminals in general are not. Batteries are generally located in an area of the vehicle where sheet metal is easily displaced and can come in contact with these exposed terminals. A short circuit at the battery terminals is current limited by the external circuit and the internal battery impedance of a few milliohms. This can result in a short circuit current in excess of 500 amperes for a short period of time. This is in excess of the level produced with an arc welder in many cases. Therefore, short circuits of a battery appear extremely hazardous if fuel is available for ignition. Metal need not only deform around the battery, but the battery may also break loose and short circuit to anything it might contact.

Fiat researchers (Reference 13) investigated the possibility of a battery still being able to produce current after the case has been broken and the electrolyte drained out. There were cases where, an hour after damage occurred, current was still available at the terminals and the battery still provided a dangerous spark source.

3.2.4 Friction Sparks

Friction sparks present another possible ignition source. These are burning or hot metal particles which have been abraded from part of the vehicle during an accident. For friction sparks to be present, a metallic part of the vehicle structure must come in contact with the pavement. There are three basic material types which may provide friction sparks in a vehicle impact. The most prevalent material available is low carbon steel, used in frame and sheet metal parts. Cast iron used in brake drums and housings and spring steel in the vehicle suspension system are also possible spark sources.

Those accidents where the vehicle body or undercarriage contact the ground can provide friction sparks. The top and side of the vehicle might be involved in a rollover situation. The body or undercarriage might easily be involved in a one-car accident where the suspension collapsed or a wheel was lost. This would provide a more dangerous situation if it occurred at the rear of the vehicle since the fuel tank could be torn in this type of accident. At high speed, sparks and fuel could be available for a considerable period of time and thus provide a fire hazard longer than during a vehicle-to-vehicle impact.

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13. Locati, L., and Franchini, E., Car Crash-Fire Investigation - Indagine Sull'incendio di Vetture Causato da Collisione, paper presented at 11th Fisita Congress, Munich, June 1966.

3.2.5 Hot Surfaces

Various hot surface areas exist within the confines of a vehicle which may have high enough temperatures to induce autoignition of gasoline. The exhaust system from the manifold or headers to the tailpipe operates at high temperatures. The exhaust manifold contains the highest temperatures in pre-1975 vehicles. It is also in a location which may receive fuel spillage if a fuel line is broken. The temperature of the flange where the exhaust pipe is bolted to the manifold will be higher than the remainder of the manifold due to its larger concentrated mass.

The exhaust pipe connects to one or two mufflers in series before reaching the tailpipe. The temperature in the system decreases steadily until the tailpipe is reached. In 8-cylinder vehicles two exhaust systems will probably be available, thus, furnishing a larger area of hot surfaces than on a 4- or 6-cylinder vehicle.

American cars manufactured in the 1975 model year and later present a higher possible hazard level from the standpoint of hot surfaces than pre-1975 vehicles. This system using a catalytic converter between the muffler and the manifold is operated at a very high temperature to reduce exhaust emission and is therefore a possible hot surface igniter.

Vehicle brakes can also be a source of high surface temperatures depending on conditions just prior to the vehicle accident. For instance, if the vehicle has been coming down a long mountain grade and using the brakes frequently prior to impact, temperatures may be 800°F or higher for a short period of time and may easily be a potential ignition source. This would be true of either drum or disc brakes.

3.2.6 Engine Backfires

Although engine backfires can ignite fuel during aircraft crashes, engine backfires are not likely to occur during an automotive vehicle impact due to the short time span that the engine continues to run. Unlike radial airplane engines that may continue rotating after a crash even though the electrical ignition system is inoperative, automobile engines generally stop rather quickly. This rapid stopping does not allow fuel/air mixtures to enter or build up in the hot cylinders for any length of time after the impact. In addition, the high exhaust collector temperatures encountered in aircraft are not encountered in automobiles. Thus, an unburned charge can come in contact with the automobile exhaust manifold and be less likely to ignite than in an aircraft.

3.2.7 External Ignition Sources

In addition to the ignition sources available from the vehicle during an accident, external ignition sources can also be available. As the direct result of an accident, a high-tension line may be broken and drop to the ground, providing an excellent ignition source of 12,000 volts or more. Adequate energy is most certainly available in a spark source of this nature. Highway flares may be another possible ignition source. This may be especially true if they are set out by an inexperienced individual who comes upon the scene of an accident and does not realize gasoline is being spilled from the fuel tank.

An additional external ignition source which can be either in the vehicle or contributed from outside is a burning cigarette. Some speculation is involved as to whether a cigarette can actually cause a fire or not since the Fiat researchers (Reference 13) were unable to ignite gasoline with a burning cigarette during laboratory tests.

3.3 SPARK ENERGY LEVELS

3.3.1 Minimum Ignition Energy Levels

A spark requires a certain minimum energy level to ignite a fuel mixture. Figure 3-1 shows energy levels required for ignition of typical hydrocarbon compounds based on fuel/air ratio. It can be seen that, although the ignitable fuel/air ratio varies

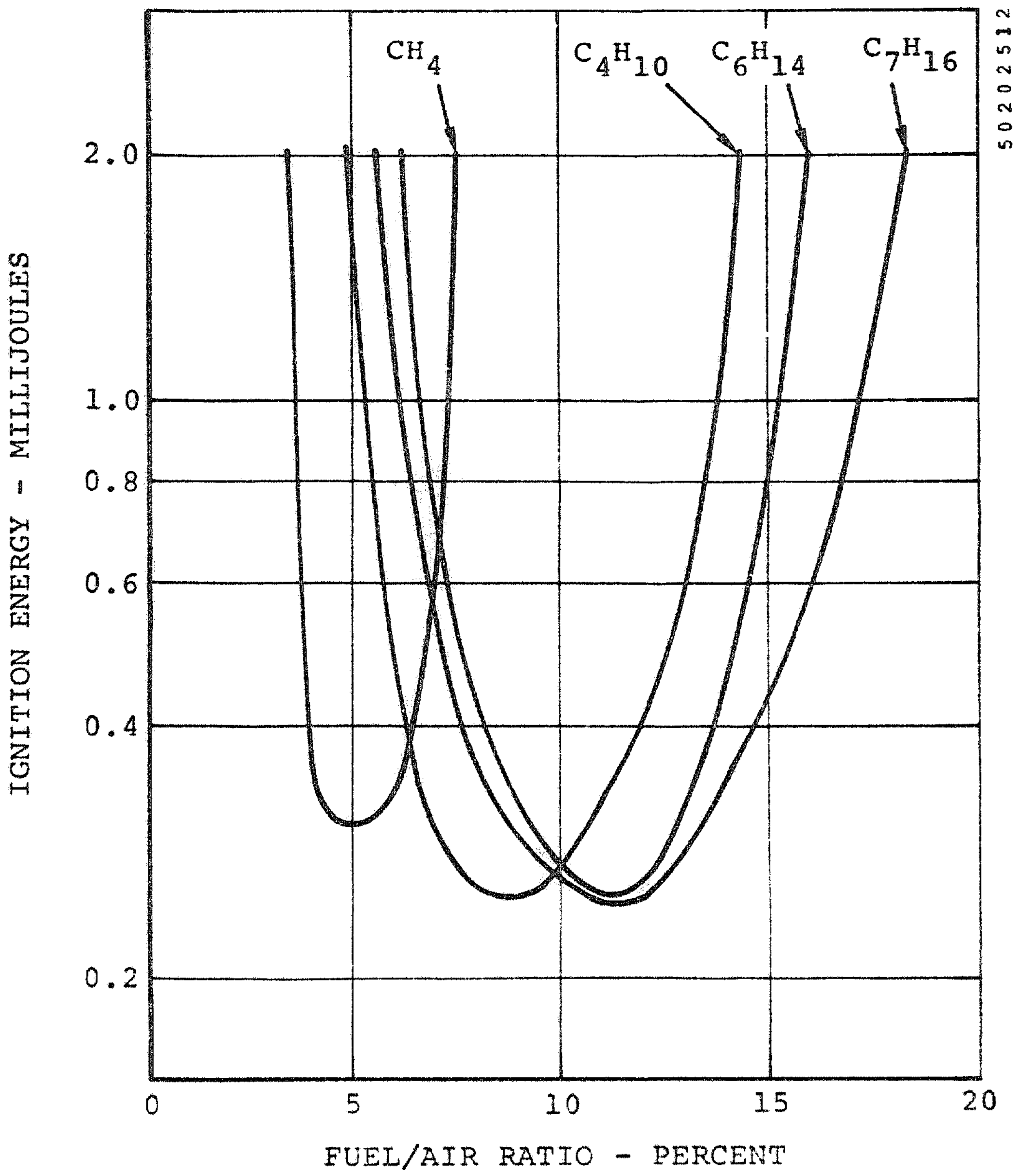

Figure 3-1. Critical Dependence of Ignition Energy on Fuel/Air Ratio for Typical Hydrocarbons.

considerably for the different compounds, the minimum ignition energies required are all within 0.1 millijoule of each other. This minimum energy level is affected by a number of variables which include mixture composition, pressure, temperature, spark duration, and electrode configuration (size, material, and spacing). The following sections discuss the properties of the specific types of sparks which might be encountered during a vehicle crash.

3.3.2 Inductive Sparks

Sparks of this nature occur when a wire is broken in an inductive circuit. The sparks are generally not as bright as capacitance sparks and exhibit a spectrum which corresponds to the electrode material. Also, spark duration will be long compared to a capacitance spark, and therefore, the energy transferred in an inductive spark can be somewhat greater. The following formula indicates the total energy which is dissipated in a circuit of this type when there is a spark.

$$E = \frac{Li^2}{2} \qquad (3\text{-}1)$$

E = energy dissipated in joules

L = inductance of circuit in henrys

i = current in amperes in circuit prior to release

Although it would appear easy to determine which inductive energy sources are a hazard by simple measurements, this is not so. Energy dissipated may be higher than indicated from calculations if the potential across the electrode gap is adequate to maintain the spark. Also, the energy may be less if the spark is extinguished before all the energy in the circuit is dissipated. Thus, a strictly analytical approach may be inadequate to determine if a particular vehicle component is hazardous.

An inductive spark differs from a capacitance spark in that it is affected by the electrode material. In general, as the density of the electrode material is decreased, the energy required to ignite a fuel mixture decreases. The energy level change is not great, and since virtually all vehicle wiring is done with copper, this factor can be ignored in the present study.

Data were not available to determine the effect of electrode spacing on spark energy for inductance sparks; however, it is of relatively little importance in an automotive investigation. An inductance spark will be generated when a wire is broken or shorted to ground. Due to the dynamics of the situation, gaps from zero to an undetermined distance will be available over a short or long time frame. If a wire is broken in a crash, the gap spacing is an uncontrollable factor.

Another factor to be considered in an inductive circuit is whether current type has any effect on the energy levels available for ignition. Tests which have been performed (Reference 14) indicate that current type (DC or AC) does not affect the energy levels necessary for ignition.

It can be seen that many factors affect the ability of an electrical component and its surrounding environment to provide a spark energy level adequate for ignition. However, once the inductive component is placed in the system, all other factors that have an effect on ignition energy levels are for all practical purposes uncontrollable during the crash environment.

3.3.3 Capacitive Sparks

Sparks of this nature exhibit totally different characteristics from inductive sparks. They are usually much brighter and of a shorter duration than inductive sparks. The spectrum which is exhibited corresponds to that of the gas mixture which is present. Although the current levels in capacitive sparks can be quite large due to their short duration, the energy level can be quite low. The following formula indicates the energy available for ignition in discharging a circuit where capacitance is present.

$$E = 1/2C(V_2^2-V_1^2) \qquad (3-2)$$

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14. Scull, Wilfred, Relation Between Inflammables and Ignition Sources in Aircraft Environments, NACA Report No. 1019, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, 1951.

E = energy dissipated in joules

C = capacitance in farads

V_1 = extinction potential, after spark has been dissipated as a result of weakening field (volts)

V_2 = potential immediately prior to spark (volts)

Although both equations for inductive and capacitive spark energy are structurally the same, available circuit inductance can easily be larger than capacitance by a factor of 1,000 or more. However, the available spark energy from a capacitor is 25 times larger than from an inductor of the same size.

Studies of electrode configuration show a minimum energy is required for ignition when the electrode is sharp in comparison to a spherical test electrode. Wire breaks will, of course, exhibit this configuration rather than the spherical surface which is used in laboratory experiments.

While electrode spacing on inductive sparks is not a well known quantity, it has been carefully investigated in capacitive spark systems. If the electrodes are very close together, the required energy for ignition rises rapidly because the electrode mass exerts a cooling effect which quenches the initial inflammation. Once this quenching distance between the electrodes is exceeded, the minimum energy required to ignite a fuel/air mixture is reached and remains relatively constant for a short distance. In an automobile collision the electrode gap is not controllable. Since energy is a function of gap space, the minimum energy level will be attained sometime during the crash if a wire is broken and/or grounded.

The electrode material has no significant effect on capacitive spark energy as it does on inductive sparks.

Another type of capacitive spark is an electrostatic spark. This type spark is caused by contact of two unlike surfaces and is accumulated as a result of friction. This can be induced during an impact or as the result of airflow with a heavy dirt content such as in a dust storm. The available energy levels and hazards of this type of spark for ignition purposes in an automobile are not known.

The production of electrical sparks and their ability to ignite a fuel/air mixture are complex subjects. The area has been summarized in this section only to impart some idea of the mechanism which is responsible for ignition in a majority of vehicle fires. Refer to Reference 14 for a comprehensive investigation of the subject.

3.3.4 Friction Sparks

Friction sparks may also be produced in a vehicle accident and are quite different from electrical sparks. They are actually small particles of metal abraded from the parent material. In an automobile they would generally consist of mild steel although cast iron, spring steel, and possibly aluminum could be present. These small pieces of metal are torn away and heated as a result of friction. When they contact the air, they oxidize or burn. Tests have shown (Reference 14) that the temperature of small heated spheres must increase rapidly as the size diminishes in order for ignition to take place. This increase in temperature may be accomplished by increasing the bearing pressure and maintaining that pressure for a specific length of time in order to preheat the parent material and thus increase the spark energy. Basically, friction sparks are rather poor ignition sources due to their small size in relation to their surface temperature. The energy level of friction sparks from ordinary materials found in automobiles is quite low. However, titanium and magnesium alloys generate high-energy friction sparks and must be considered dangerous. At the present time these materials are not used in automobiles except for a relatively small number of optional magnesium alloy wheels.

3.4 GASOLINE AND FLAMMABLE MATERIAL CHARACTERISTICS

3.4.1 General Properties of Gasoline

The following description of the properties of gasoline was taken from the Third Edition of Dangerous Properties of Industrial Materials (Reference 15).

Synonym:	Petroleum
Description:	Clear, aromatic, volatile liquid
Formula:	A mixture of aliphatic hydrocarbons
Constants:	Flash point: -45°F, density: <1.0, vapor density: 3.0-4.0, Underwriters Laboratory Classification: 95-100, lower explosive limit: 1.4 percent, upper explosive limit: 7.6 percent, autoignition temperature: 495°F
Fire Hazard:	Dangerous when exposed to heat of flame; can react vigorously with oxidizing materials.
Explosion Hazard:	Moderate, when exposed to heat or flame.
Disaster Hazard:	Dangerous, in the presence of heat or flame.

3.4.2 Flash Points of Gasoline and Oil

The flash point of a substance is the minimum temperature at which vapors from the material will propagate a flame away from the source of ignition. The flash point of gasoline varies from -45°F to -36°F depending on the octane number. Thus, gasoline can flash in virtually all parts of the country, even in the winter, if an ignition source is present.

Engine oil, on the other hand, has a flash point that is much higher. The flash point of engine oil is in the range of

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15. Sax, Irving N., Dangerous Properties of Industrial Materials Third Edition, Radiological Sciences Laboratory, New York State Health Department, Albany, New York, Reinhold Book Corporation, New York.

400° to 500°F. The flash point of oil is not reached even under heavy driving loads, but it can be reached if the oil comes in contact with a hot manifold or catalytic converter.

3.4.3 Combustible Range

Gasoline cannot be defined by one particular equation as many chemical substances are. Gasoline is composed of hydrocarbons ranging from C_5H_{12} to C_9H_{20}; thus, different mixtures or blends represent different properties. Figure 3-2 shows the relationship of the fraction of stoichiometry to the required ignition energy for five hydrocarbon fuels of which two fit into the gasoline range. The fraction of stoichiometry may be converted to a more meaningful one of fuel/air ratio (by weight) with the following formula:

$$F/A = (\text{fraction}) \frac{14n + 2}{216n + 62} \qquad (3\text{-}3)$$

where n represents the carbon subscript associated with the equation:

$$C_nH_{2n+2} + \frac{3n + 1}{2} O_2 + (6n + 2)N_2 =$$

$$nCO_2(n + 1)H_2O + (6n + 2)N_2 \qquad (3\text{-}4)$$

As may be seen from Figure 3-2, ignition of a fuel is dependent on its ability to form combustible fuel-to-air mixtures in the vapor phase. Ignition will not occur unless certain fuel/air ratios are present in the surrounding crash environment. For gasoline, this condition "can" exist for all temperatures above approximately -40°F. However, even ignition of fuel-in-air vapors must occur within certain flammable limits. For gasoline, ignition can only occur for fuel/air mixtures (percent by volume) between 1.4 and 7.6. These lower and upper values represent the limits below and above which ignition will not occur for any amount of igniter energy.

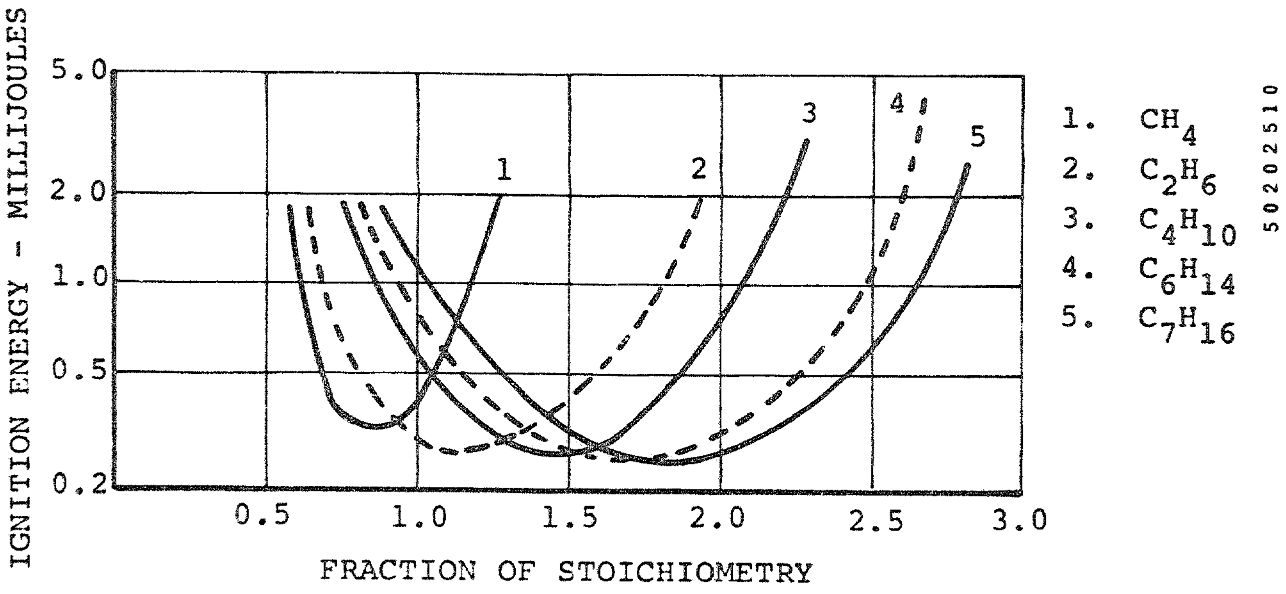

Figure 3-2. Critical Ignition Energy for Several Hydrocarbon Fuels.

3.4.4 Autoignition Properties

The autoignition temperature of a substance is the minimum temperature required to initiate or cause self-sustained combustion independently of the heating or heated element. The reported autoignition temperature (AIT) of gasoline is 495°F. This temperature measurement is rather ambiguous inasmuch as many factors affect autoignition. For example, the ignition temperature of hexane as determined by three different methods yielded results from 437° to 950°F (Reference 16). Some of the factors which affect this are size and shape of container, method of heating, container material, rate and duration of heating, fuel mixture, and fuel mixture flow rate. The data in Figure 3-3 and Tables 3-1 and 3-2 show the AIT of several hydrocarbons and indicate variations in temperature due to the different test conditions noted. Although gasoline is not listed, the variations noted are typical of all hydrocarbon fuels.

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16. National Fire Codes, Volume 1, Flammable Liquids, National Fire Protection Association.

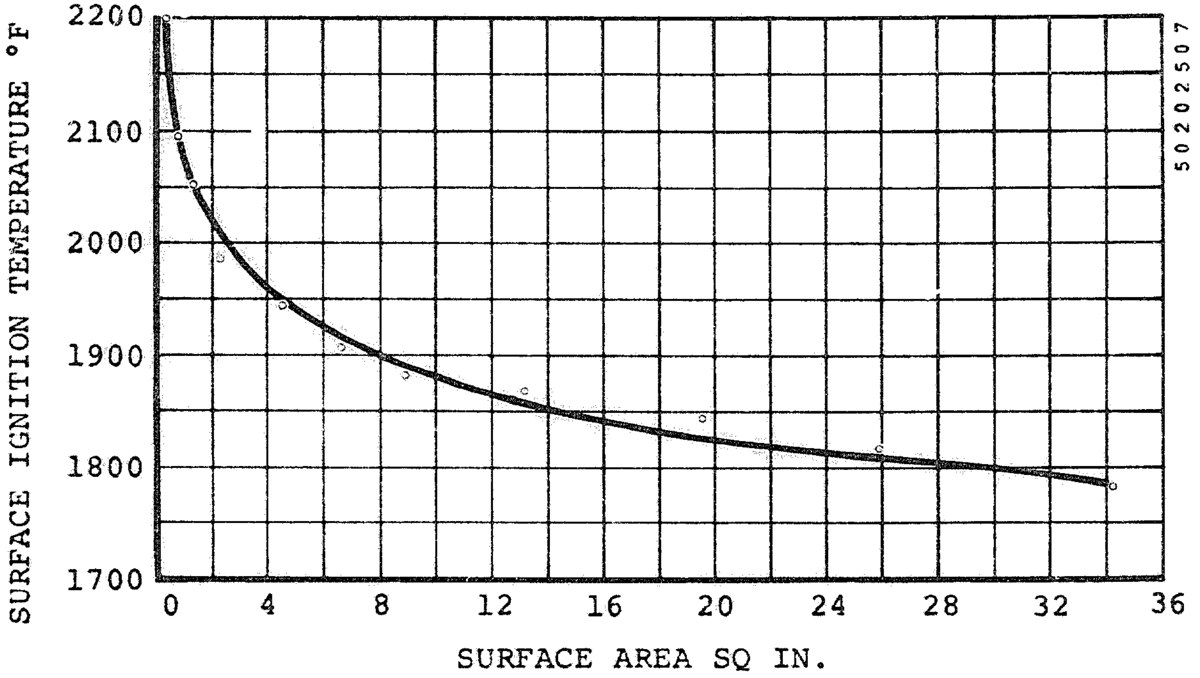

Figure 3-3. Effect of Surface Area on Surface Ignition Temperature of Quiescent 7-percent Mixture of Natural Gas and Air. Ignition Surface, Electrically Heated Nickel (Data from Reference 14).

TABLE 3-1. MINIMUM AUTOIGNITION TEMPERATURE OF N-OCTANE, JP-6 FUEL, AND MIL-L-7808 ENGINE OIL IN 1.16 IN.^{3} CYLINDRICAL VESSELS WITH QUIESCENT AIR AT ATMOSPHERIC PRESSURE

	Autoignition Temperature, °F		
Vessel Material	n-Octane	JP-6	MIL-L-7808 Engine Oil
Pyrex	990	945	940
Stainless Steel	995	995	1015
Aluminum	1080	1060	1090
Carbon Steel	1155	-	-

Vessels - 0.5 inch diameter, 6 inches long.
Fuel-oxygen ratio ∿ 1 (data from Reference 17).

TABLE 3-2. MINIMUM AUTOIGNITION TEMPERATURES OF FOUR HYDROCARBON FUELS AND AN ENGINE OIL IN SPHERICAL PYREX VESSELS WITH QUIESCENT AIR AT ATMOSPHERIC PRESSURE* (IGNITION CRITERION - APPEARANCE OF FLAME; FUEL-OXYGEN RATIO - 1)

Vessel Volume (cc)	Vessel Volume (in.^{3})	Vessel Diameter in.	S/V** (in.$^{-1}$)	S (in.^{2})	Autoignition Temperature, °F n-Hexane	n-Octane	n-Decane	JP-6	MIL-L-7808 Engine Oil
5	0.305	0.94	7.19	2.18	1110	1025	1000	1000	1020
[illegible]	0.610	1.05	5.73	3.49	950	875	800	805	880
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	770	755	810
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	640	535	490	525	780
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	500	470	500	780
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	450	425	485	755
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	440	420	470	755

*Data from Reference 17.
**Surface area to volume ratio of vessel.

In addition to the variables cited above, a delay time is required so that adequate thermal energy may be added to ignite the substance in question. This can take 60 seconds or longer even in low AIT temperature regions.

The hot surface or autoignition temperature is difficult to relate to the hot surfaces of an automobile. With large variations found under laboratory conditions, one can easily imagine the difficulties associated with determining their effect in an automobile.

3.4.5 Hot Gas or Open Flame Ignition

Gasoline may also ignite as the result of being exposed to hot gases or an open flame. Gas temperatures greater than 1,300°F would probably be required to ignite gasoline since temperatures in the range of 1,220°F to 1,280°F minimum are required for ignition of n-hexane, n-octane, and n-decane (Reference 17). Hot

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17. Kuchta, J. M., and Cato, J. J., Ignition Characteristics of Fuels and Lubricants, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, for the Bureau of Mines, No. AF APL-TR-65-18, March 1965.

gases are available at the exhaust of an automobile engine; however, they would only be available to contribute to ignition if the manifold were broken very close to the engine head. A break at this point would probably indicate an accident of severe enough nature to stop the engine and thus stop hot gas flow.

3.5 VEHICLE AND ENVIRONMENTAL TESTING

A laboratory testing program was planned to define the conditions under which motor vehicle ignition sources present in crash situations would ignite spilled fuel. Prior to conducting the laboratory tests, it was necessary to determine roadway and vehicle surface temperatures to which the spilled fuel might be exposed during and immediately following the crash.

3.5.1 Asphalt Surface Temperature Testing

To determine a criterion for fuel temperature to be used in the upcoming laboratory ignition tests of spilled fuel, asphalt surface temperatures were measured. These measurements were taken with a thermocouple set just below the surface in three different locations at the Ultrasystems' facility in early September. Temperatures at this time of the year in Arizona had decreased from highs in June and July of 118°F; however, Figure 3-4 shows that the daytime temperature reached 107°F which is higher than most of the rest of the country throughout the summer months. Asphalt temperatures reached 124°F. (Concrete temperature measurements were not taken since the color of concrete is lighter than that of asphalt so its ability to absorb radiation would be less.)

In the earlier part of the summer months the sun is 20° higher in the sky and incoming solar radiation is much greater. Asphalt temperatures in the area of 140°F would not be uncommon. Thus this temperature was selected as the maximum temperature for pooled fuel during the laboratory tests.

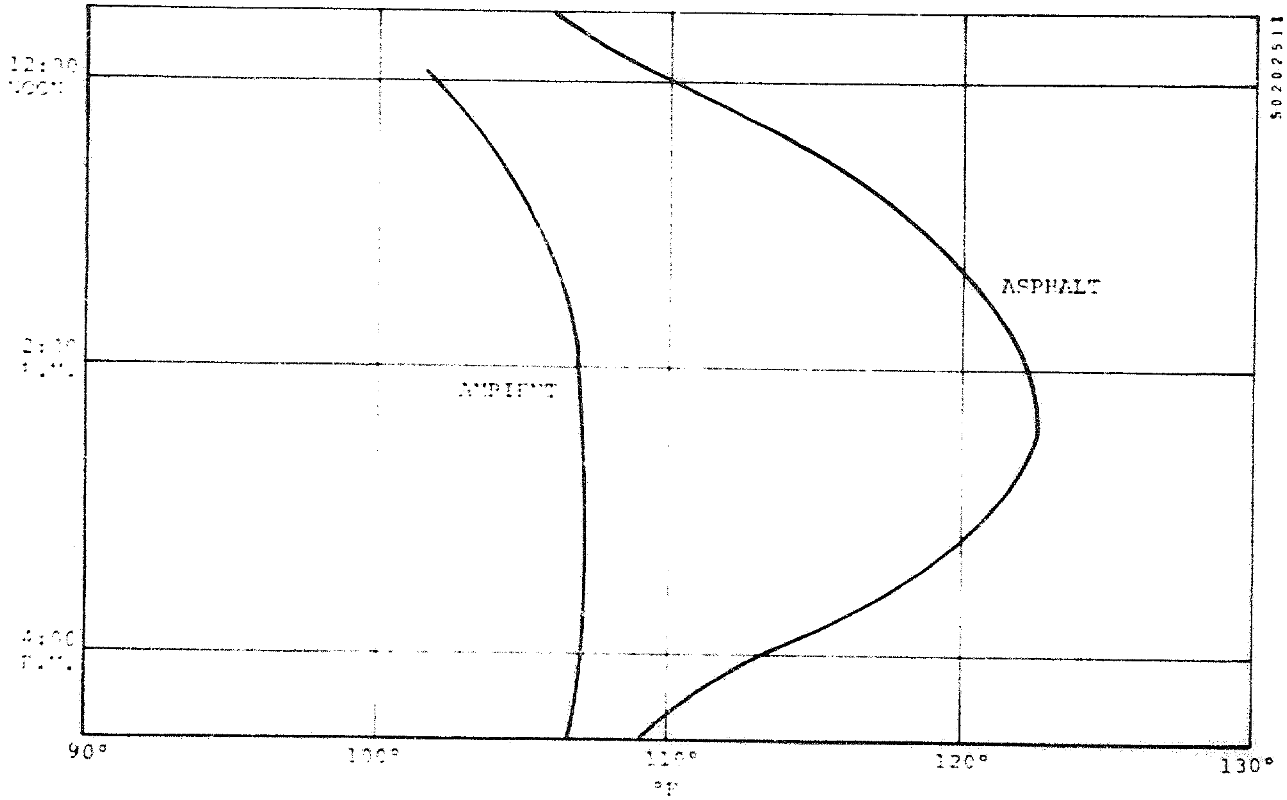


Figure 3-4. Asphalt and Ambient Temperatures Measured at Ultrasystems' Facility.

3.5.2 Vehicle Surface Temperature Testing

Vehicle temperature measurements were also taken to determine if hot areas of the vehicle exhaust system would be adequate to ignite gasoline by autoignition. Three 1974 American automobiles were tested.

The test vehicles were warmed up on a two-mile oval test track for 15 minutes at 40 miles per hour. The ambient temperatures taken during these tests were in excess of 94°F; two vehicles were tested when it was 104°F. Again, these temperatures were much warmer than the average the rest of the country will see throughout the summer. The exhaust system temperatures were obtained with a thermocouple. All vehicles were idle during the temperature measurements.

Figure 3-5 shows the results of these tests. It is doubtful that these temperatures would lead to autoignition of gasoline. However, temperatures somewhat higher than these can be expected at higher engine output levels when the vehicle is accelerating or under load.

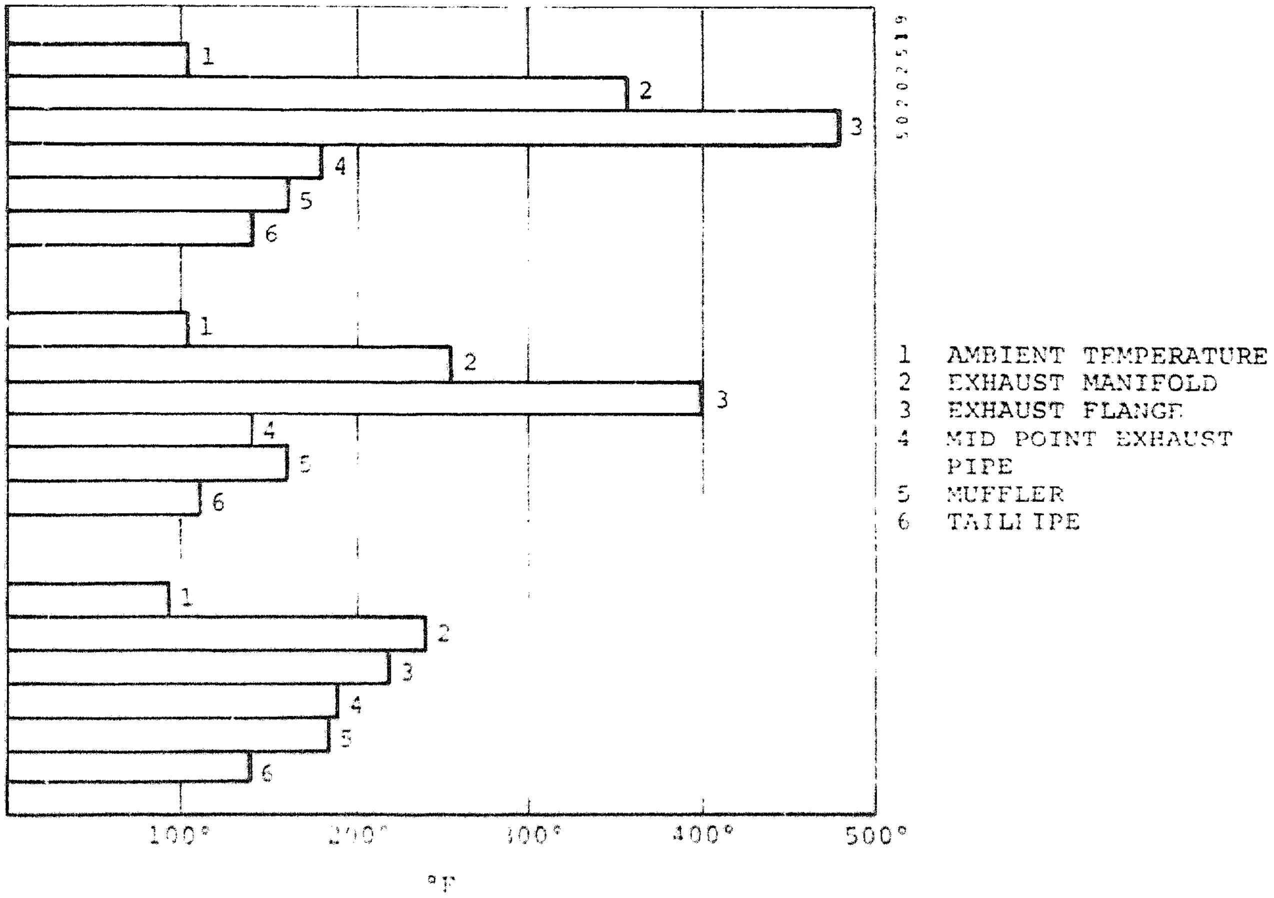


Figure 3-5. Exhaust System Temperatures - 1974 Test Vehicles.

In 1975 vehicles the exhaust system includes a catalytic converter. This device is used to reduce exhaust gas emissions to an acceptable level to meet Federal emission standards. Temperatures on the surface of the converter can reach 1,000°F under certain conditions; therefore, this system must be considered a possible gasoline ignition source. Figure 3-6 shows temperatures on the

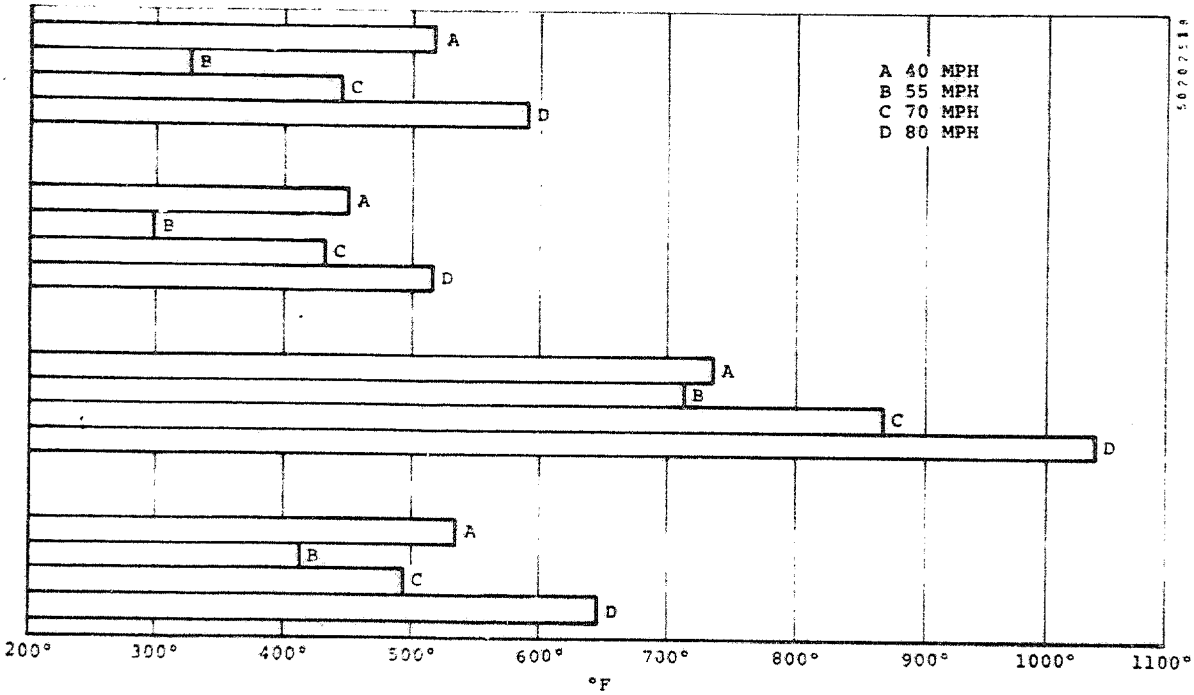


Figure 3-6. Catalytic Converter Temperatures - 1975 Vehicles.

converter measured during various operating conditions. The 55-mph temperatures are lower since the vehicle was started up cold for tests at this speed while the vehicle had been running prior to testing at the other speeds.

3.6 LABORATORY TESTING OF IGNITION SOURCES

A series of laboratory tests was conducted to define the conditions under which motor vehicle ignition sources present in crash situations would ignite spilled fuel and to determine which of the many ignition sources are the most hazardous. The test program not only considered all potential ignition sources but also the pooled fuel environment and physical environment of the vehicle. The ignition sources consisted of electrical sparks, hot surfaces, and minute hot surfaces such as lamp filaments and friction sparks. The pooled fuel environment consisted of varying fuel temperatures and surface areas. The physical environment ranged from an open environment to varying degrees of a restricted environment.

The general procedure consisted of placing predetermined quantities of gasoline in a dish and allowing the gasoline to evaporate. The concentration of the vapors formed decreased with increasing distance from the surface. The ignition source was lifted away from the surface so that it could not fail to cross a point where the vapor concentration was in the flammable region. In addition, the same tests were conducted by lowering the ignition source toward the surface. The two sets of values delineated the flammability mixture band width critical for that particular ignition source. The wider the band, the more energy contained in the ignition source and the more hazardous it is.

The following sections present detailed descriptions of the test apparatus, procedures, and results.

3.6.1 Electrical Ignition Sources

3.6.1.1 Test Equipment and Procedures

The test apparatus is shown in Figure 3-7. It consisted of an electrode assembly, a vertical drive motor, a spark generating system, and a hot plate.

The electrode assembly consisted of two copper rods four feet long inside two pyrex tube insulators mounted on either side of an aluminum bar. Copper wire electrodes were mounted at the lower end of each copper rod with set-screws as shown in Figure 3-8. One of the copper rods was stationary while the other could be rotated through about 45° of arc and then returned to its rest position by a return spring, thus making and breaking contact between the two electrodes. This arrangement simulated both momentary shorts from broken wires and the breaking of a wire.

The rotating electrode was actuated through a cam driven by an air motor. The air motor received air for operation through a bottled air supply. The speed of the motor and consequently the spark rate were governed by a regulator which controlled the air pressure fed to the motor.

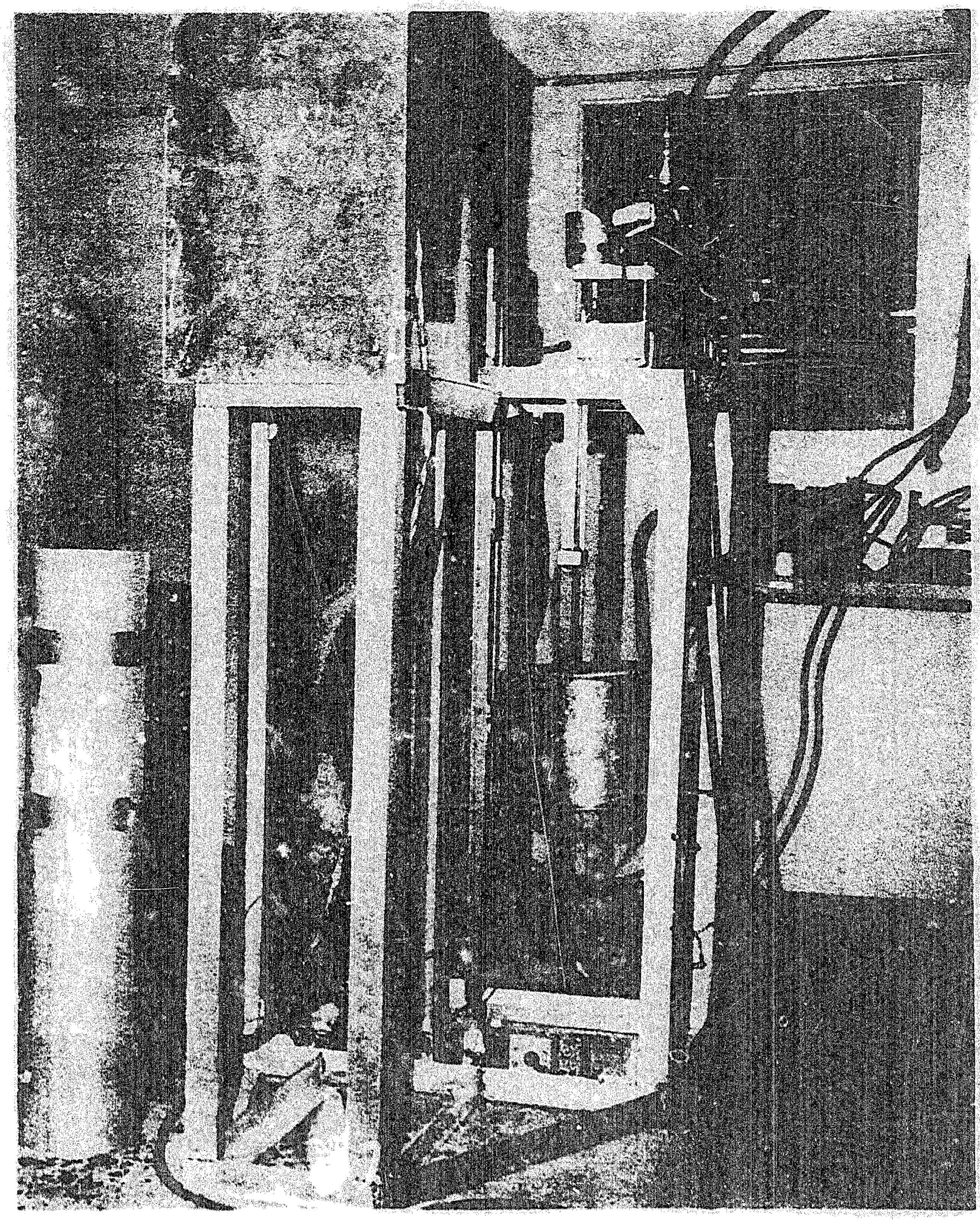


Figure 3-7. Laboratory Ignition Source Test Apparatus.

The whole electrode assembly could be moved vertically from the fuel surface to three feet above the fuel surface. This was done through a variable speed motor mounted in a protective box on top of the unit. Vertical speed during testing was adjusted to approximately .25 inch per second. This guaranteed that the reaction time of the operator would be fast enough to stop the electrode movement within .125 inch after observing ignition. Figure 3-9 shows the vertical drive unit and the electrode rotator assembly.

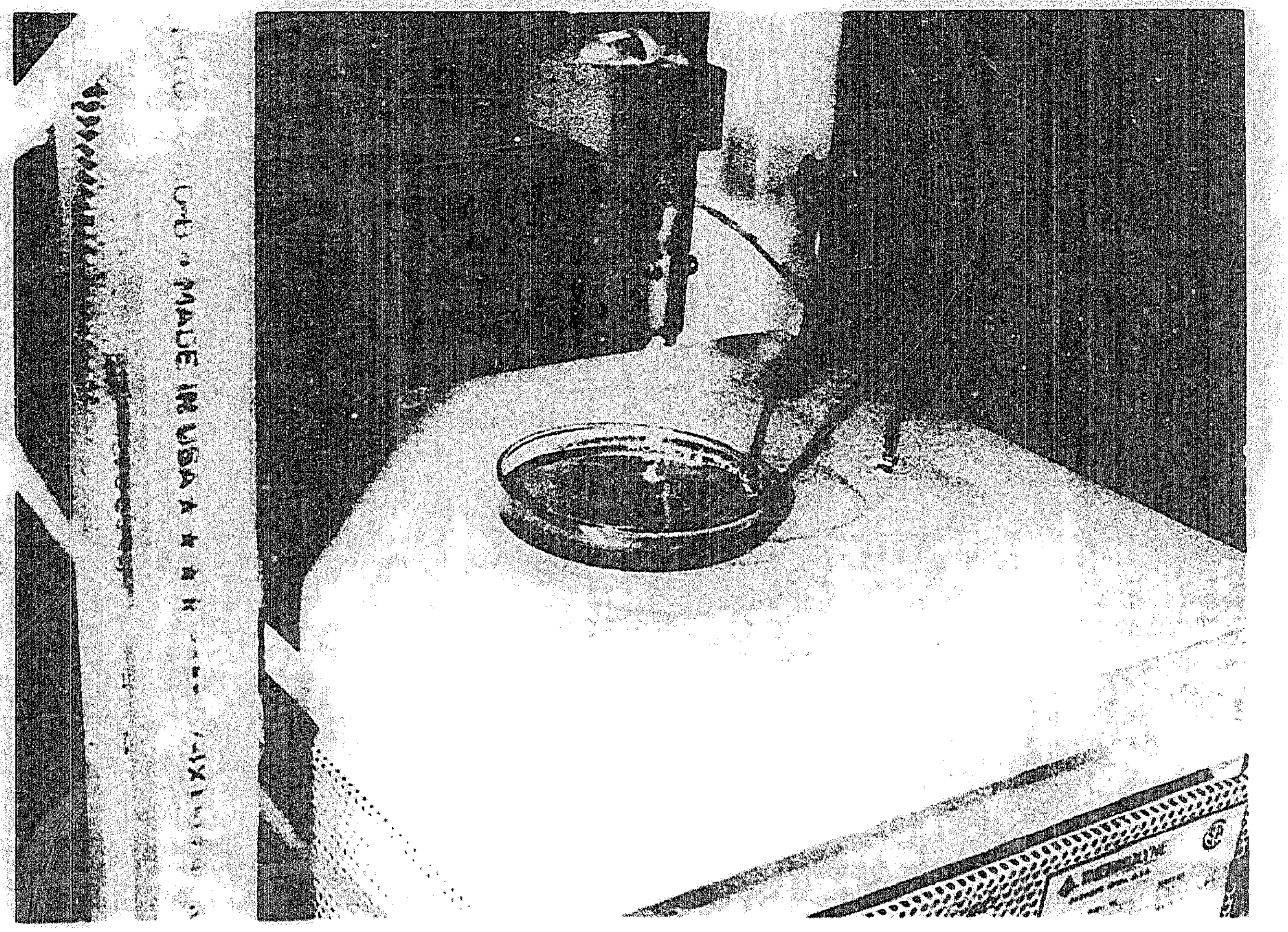


Figure 3-8. Electrode Assembly.

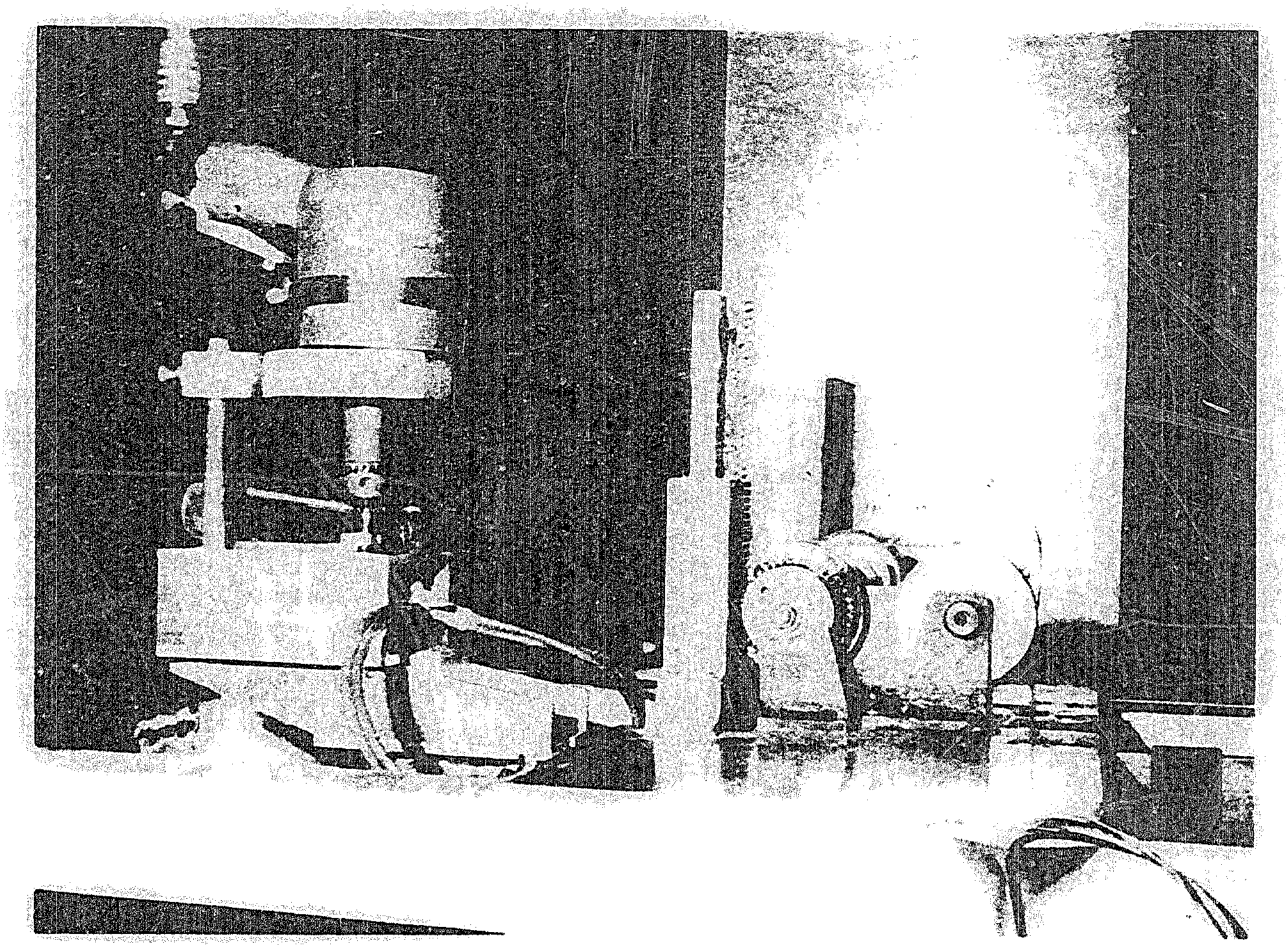


Figure 3-9. Vertical Drive Unit and Electrode Rotator Assembly.

The apparatus was operated from a control booth situated outside the laboratory. The booth contained all instrumentation monitors and operating controls. A 50-pound CO_2 fire extinguisher whose nozzle was attached to the test stand was also operated from the control booth. An observation window was used by the operator to monitor the tests.

Tests were conducted using four different fuel surface areas. Glass dishes with diameters of 60mm, 100mm, and 150mm were used to attain three different areas. The dishes contained 25cc, 75cc, and 150cc of regular gasoline, respectively. The fourth area simulated an infinite spilled fuel area which would be encountered in a massive fuel tank rupture. This was accomplished by using the

150mm diameter dish and placing a 3-foot-long 7-inch I.D. aluminum tube over it. (The tube is shown on the left side of the test stand in Figure 3-7.) Vapors building up inside this tube simulated the same type of buildup encountered with a large area of fuel. The electrode assembly moved up and down inside the tube.

Three different fuel environments were also used during the testing; first, a completely open environment with all four fuel surface areas, second, an inverted pan 12 inches in diameter by 10 inches deep, located 6 inches above the fuel surface, and third, the same pan 12 inches above the fuel surface. These latter two conditions simulated gasoline vapors being trapped under the vehicle and thus possibly generating a more dangerous vapor level than would be encountered in a completely open environment. The latter two conditions were only used with the three smaller fuel areas. Extremely hazardous conditions would have been encountered if the infinite area was tested on a closed basis. Another condition was also used with each closed environment. A strip heater was located inside the inverted pan and heated to 700°F to simulate a hot engine component.

Most of the tests were conducted twice using two different fuel temperatures. These were the laboratory ambient temperature, which was generally 68° and 79°F, and a higher temperature between 125°F and 145°F. The higher temperature was typical of asphalt temperatures on a hot day in the Southwest and was attained by heating the fuel on the hot plate.

The test apparatus was instrumented with four thermocouples which measured fuel temperature, hot plate temperature, heater strip temperature (if applicable), and air temperature inside the tube used to simulate infinite fuel areas. The thermocouple was required in the tube to determine when ignition occurred since only rarely was a flame visible at the top of the tube.

To assure that test results were as repeatable as possible, a careful time schedule was maintained in regard to fuel heating time and soak time. If the test required only ambient fuel temperature, the fuel was allowed to sit open in still air on the test stand for 2 minutes before the spark source was initiated. This assured that the fuel vapors would reach an equilibrium condition before the test was started. If heated fuel was required, it was covered and allowed to heat for 2 minutes, then uncovered and allowed to reach equilibrium for 2 minutes if an open environment was used or 3 minutes if conditions required a closed environment. This did not always result in the same final fuel temperature, because of the different volumes of fuel used, but the amount of fuel evaporation was kept constant and approximately the same amount of volatile constituents were available during each test.

The electrode assembly was alternately raised and lowered during each ignition source test to determine both the minimum and maximum heights above the fuel which would support combustion. The assembly was first lowered until it was within .06 inch of the fuel surface. The required soak time was met and the spark source was initiated. The electrodes were held at this position for approximately 3 seconds and then started up at a rate of .25 inch per second. The assembly was stopped immediately when a flame appeared or, in the case of the vertical tube, when a temperature rise was indicated. The fire was then extinguished and the final height recorded using a precision metal scale mounted on the side of the test stand and a pointer mounted on the electrode assembly. If a flame did not occur while moving the electrodes away from the fuel surface, the test was terminated since a flammable vapor mixture did not exist for that particular ignition source. However, if the fuel was ignited, the electrode assembly was raised to a position 18 inches above a fresh dish of fuel and the procedures were repeated with the electrodes being lowered toward the fuel.

3.6.1.2 Ignition Sources Tested

3.6.1.2.1 Broken Headlight Wire. Breaking a headlight wire can provide two types of ignition sources. First, tearing the headlight wire will provide a small extra-current spark due to the energy which is stored in the system. Second, grounding the voltage side of the circuit will provide a direct battery short until the wire is burned away. This particular test evaluated the extra-current spark. The direct battery short test is described in Section 3.6.1.2.4.

The test setup is shown schematically in Figure 3-10.

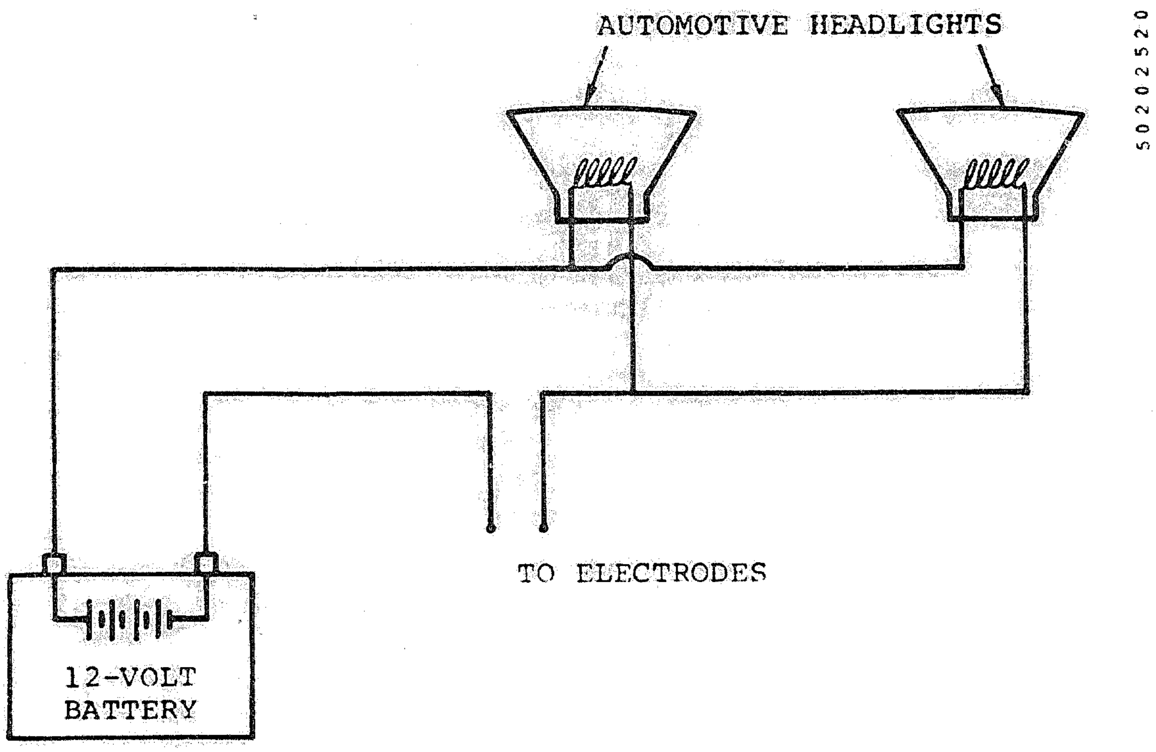


Figure 3-10. Electrical Diagram for Spark From Broken Light Wire.

Twelve volts were provided to two automotive headlamps connected in parallel. The circuit was completed when the contact points of the electrode assembly were touching. The circuit was made and broken at a rate of 4 times per second.

3.6.1.2.2 Damaged Distributor. This test investigated the potential of a discharge spark from the distributor coil functioning as an ignition source. For this to happen, the distributor cap would have to be broken while the rotor was still turning. Although one might expect the rotor to stop during impact, the fairly common incidence of distributor damage during accidents raises the possibility of the distributor acting as an ignition source which must be investigated.

The wiring diagram for this test is presented in Figure 3-11. The breaker points were removed from a distributor and the ends cut off and soldered onto a solid 12-gage wire. These modified points were then mounted on the end of the electrode assembly over a dish of fuel. The points were set to open at a rate of 4 times per second. This particular setup with an open coil output provided the largest amount of sparking energy since all the energy of the coil was discharged across the points.

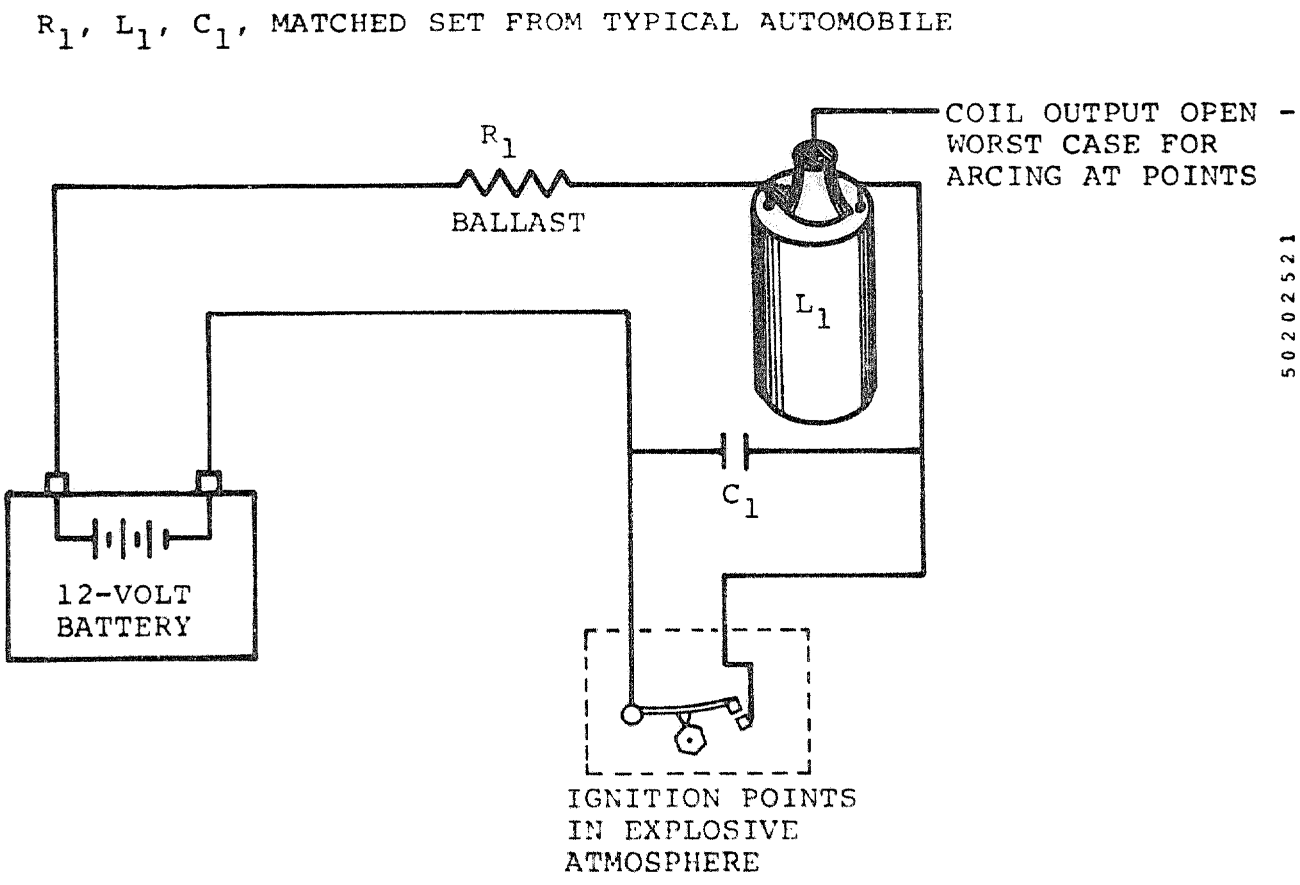


Figure 3-11. Wiring Diagram for Ignition Spark From Broken Distributor.

3.6.1.2.3 Broken High-Tension Wire. This type of ignition source would result from the breaking of a spark plug wire. This is the same source whose function in an automobile is to ignite the fuel/air mixture in the cylinder of the engine and must be considered a highly dangerous source.

A model T Ford coil was used as the spark source for these tests. This coil has a continuous high-voltage output and uses a vibrator on the end of the coil to make and break the magnetic field at a very rapid rate. The electrode gap was maintained at 0.100 inch during these tests. The schematic in Figure 3-12 shows the Ford coil as it was installed.

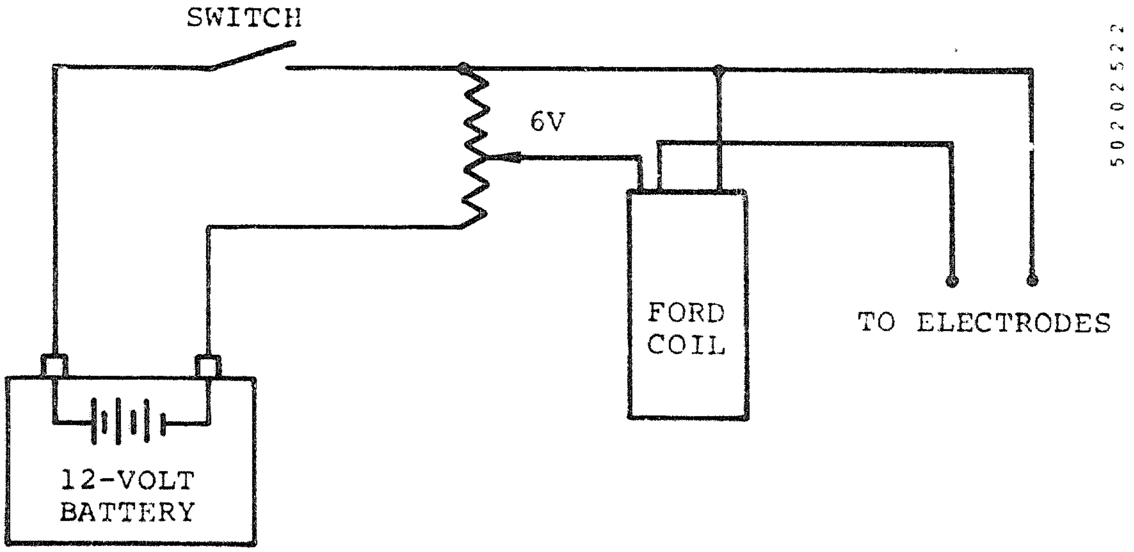


Figure 3-12. Wiring Diagram for Ignition Spark From Spark Plug Wire.

3.6.1.2.4 Direct Battery Short. A direct battery short not only occurs when a part of the vehicle structure comes in contact with the positive battery terminal but also when a hot wire is torn loose and comes in contact with a grounded area. This test used a 12-volt automotive battery with its leads going to the electrode assembly on the test fixture. All wiring was done with

Number 0 or larger cable up to the electrode shafts which were coupled to the large cable with two Number 4 wires for flexibility. The spark was formed with two pieces of Number 12 solid wire contacting through the rotating electrode.

Very bright sparks were formed with pieces of molten copper being torn away from the electrodes with each contact. Even though electrode contact was maintained for only 15 to 30 milliseconds at a time, the electrodes would generally last for only 10 to 20 seconds before they would burn off. This produced between 40 and 80 sparks.

The schematic in Figure 3-13 shows the test setup. The only limiting factor in this circuit was the internal battery resistance in the connecting cables to the electrodes.

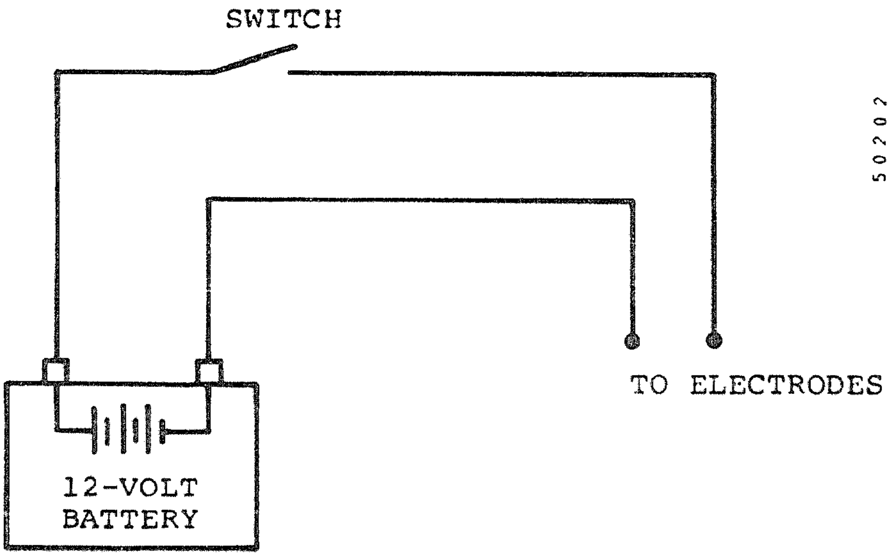


Figure 3-13. Wiring Diagram for Spark From Direct Battery Short.

3.6.1.2.5 Broken Inductive Wire. An inductive spark in general contains a larger amount of energy than a capacitive spark in a car. This test used an air conditioner compressor clutch coil to generate the required ignition spark. Figure 3-14 shows this test

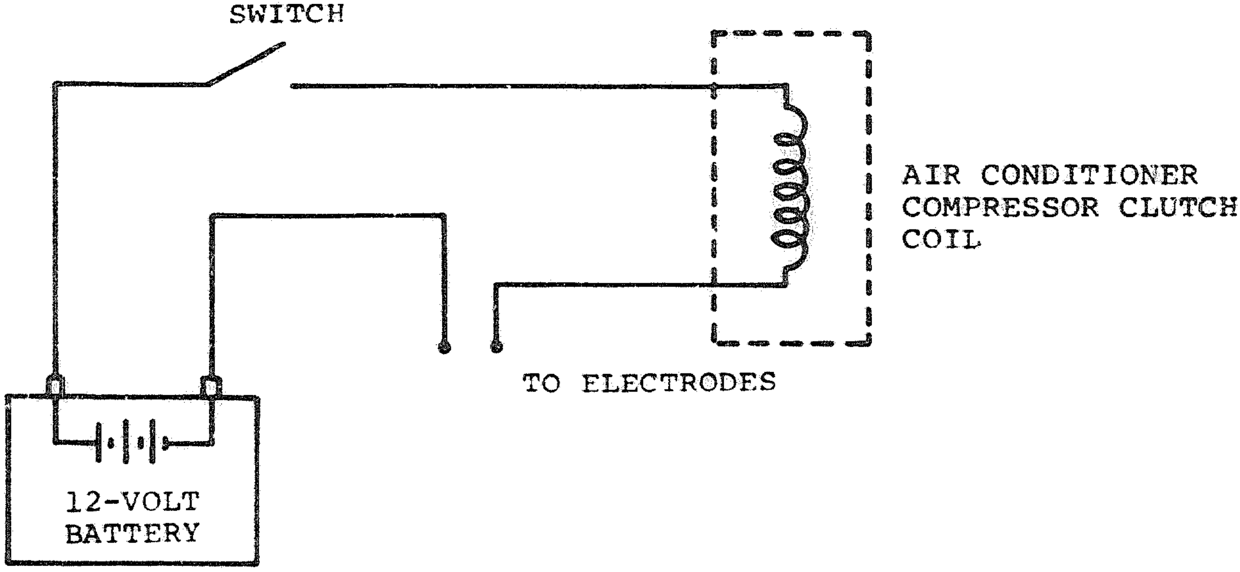


Figure 3-14. Electrical Diagram for Spark From Broken Wire From an Inductive Source.

setup. This system generated a spark when the contacts were opened and the magnetic field collapsed. This test simulated an extra-current broken wire spark and not a short circuit spark which would occur if the broken hot wire came in contact with ground (refer to Section 3.6.1.2.4).

3.6.1.2.6 Broken Headlight. The headlights were tested on the same test fixture as the other electrical ignition sources. However, their method of ignition is not due to an electrical spark but to the hot filament.

Figure 3-15 shows the wiring schematic for the headlight tests. The headlight glass was scored and carefully broken out, leaving the intact filament exposed to the air. It was found during the tests that the lamp stayed lit for a period of 1 to 35 seconds, with most lamps going out between 3 to 9 seconds as the filament burned away. However, this was an adequate time span to determine if a lighted headlamp filament would present an ignition hazard.

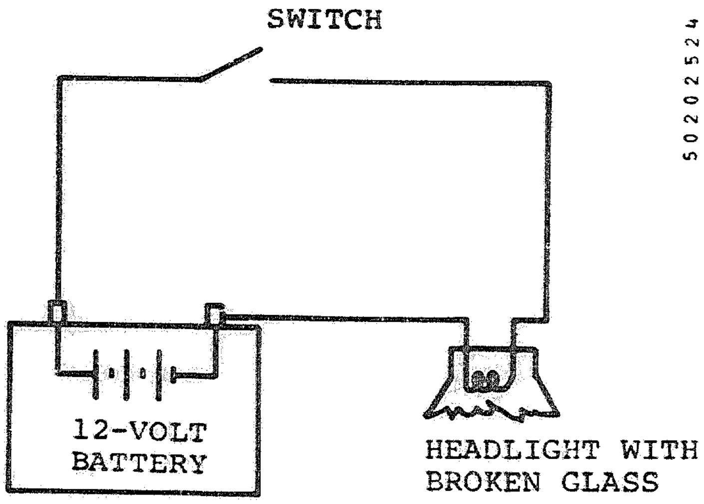


Figure 3-15. Wiring Diagram for Hot Light Bulb Filament.

3.6.1.3 Test Results

3.6.1.3.1 Electrical Sparks. The broken headlight wire and the distributor coil discharge through the ignition points did not ignite the fuel/air mixtures under any of the test conditions. Even though the spark from the distributor coil was readily visible, it still did not contain adequate energy to ignite the flammable fuel vapors.

The broken high-tension wire and direct battery short, on the other hand, ignited the fuel vapors in all of the tests. The inductive spark from the compressor coil ignited the vapors in all of the open environment tests and in 63 percent of the closed environment tests.

The test results for the three sources which ignited the fuel vapors are summarized in Figures 3-16 through 3-21. The open environment test results are presented in Figures 3-16 and 3-17. As may be seen in these figures, all three sources ignited the fuel vapors in the same general range although the areas did vary somewhat with the type of ignition source. The variations could have been caused by slightly different spark energies and also by the movement of the rotating electrode disturbing the fuel/air mixture.

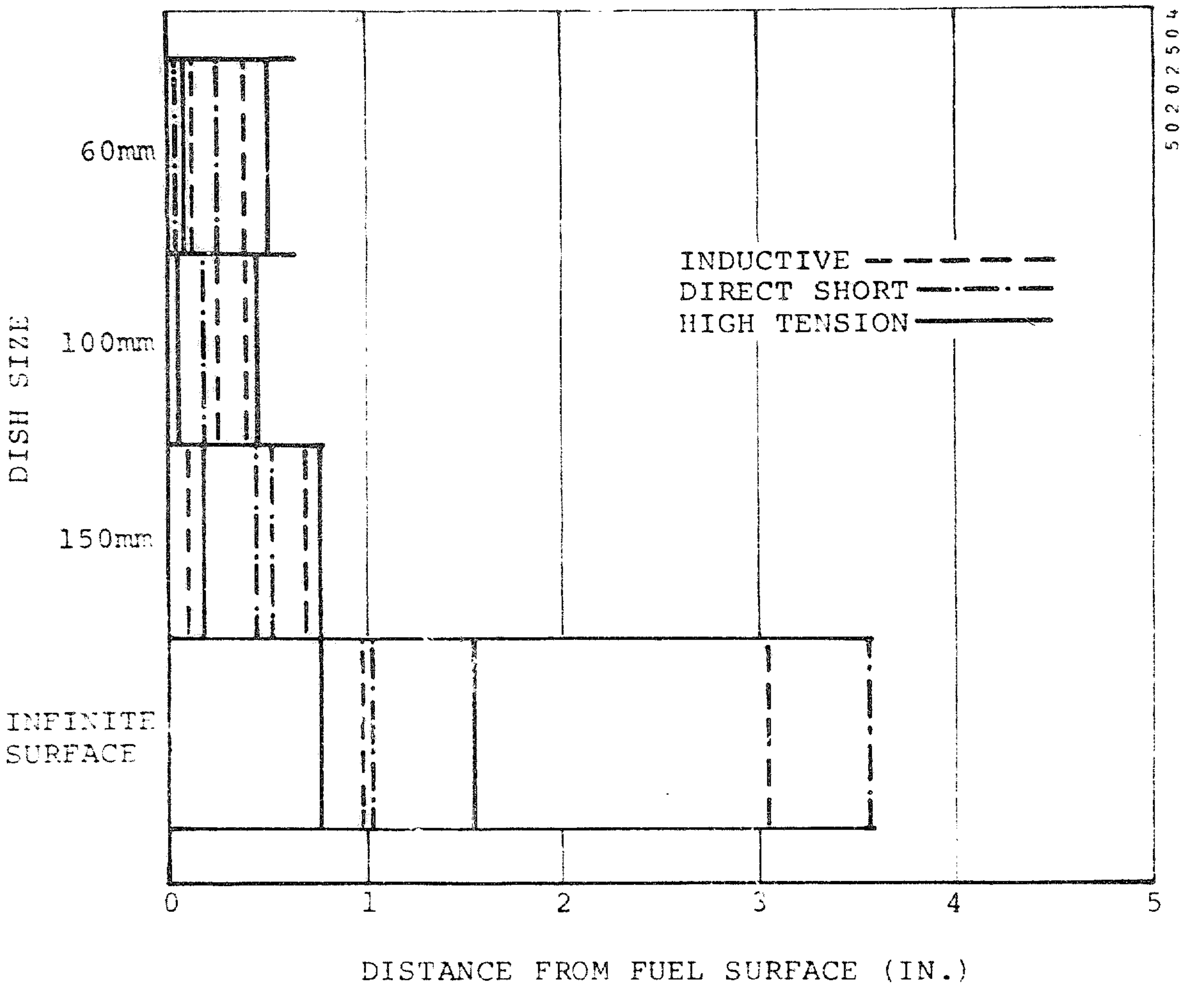


Figure 3-16. Open Environment, Ambient Fuel Temperature Ignition Bands.

The general trends of wider flammability bands for increasing fuel surface area and temperature are as expected as both of these conditions produce more fuel vapors than are produced from the smaller surface areas and lower temperatures.

The closed environment test results are presented in Figures 3-18 through 3-21. When the hood was added, the flammable ranges did not follow as consistent a pattern as they did in the open environment tests. When the hood was located 6 inches above the fuel surface, the upper limit of flammability was lowered somewhat from that found in the open environment. When the hood was

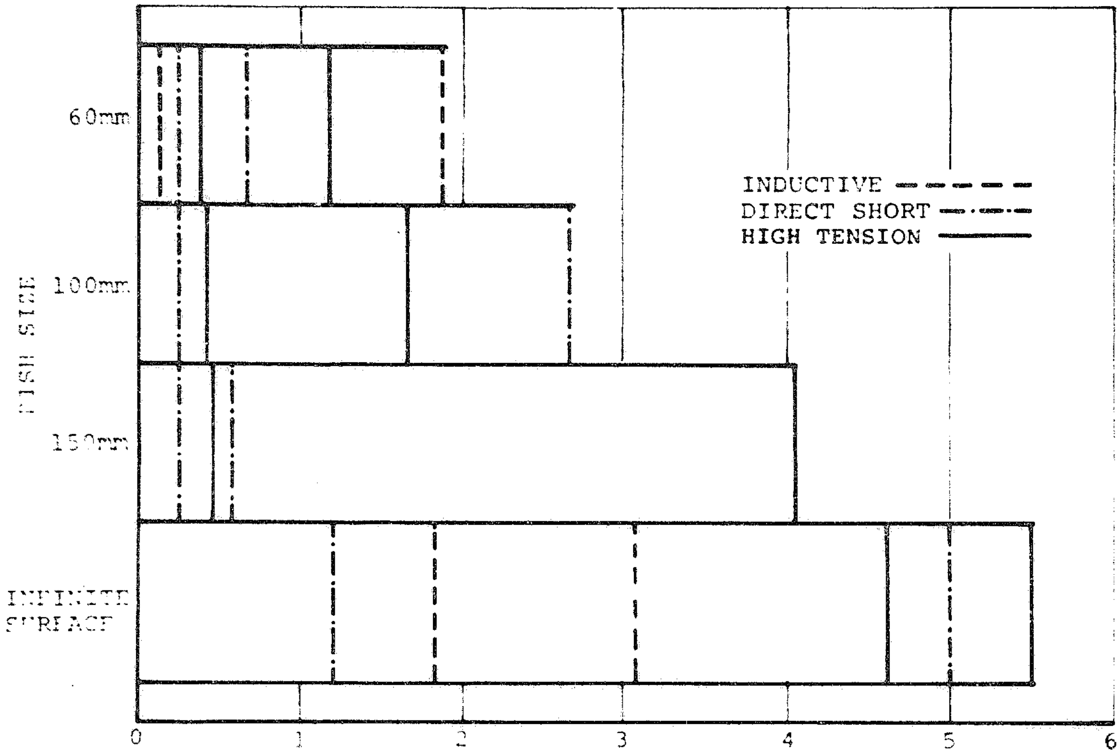


Figure 3-17. Open Environment, Heated Fuel Ignition Bands.

12 inches above the surface, this upper limit was lowered even further. The addition of a heated surface inside the hood produced some anomolous results for specific ignition sources, although the overall combined flammable band widths were not affected significantly. The unpredictable results obtained during these tests were probably due to the test conditions disturbing the equilibrium stratification of the fuel vapors in an undefined manner. However, the fact that ignition occurred even under non-equilibrium conditions emphasizes the more than sufficient energy contained in the spark sources to ignite a wide range of flammable fuel vapors.

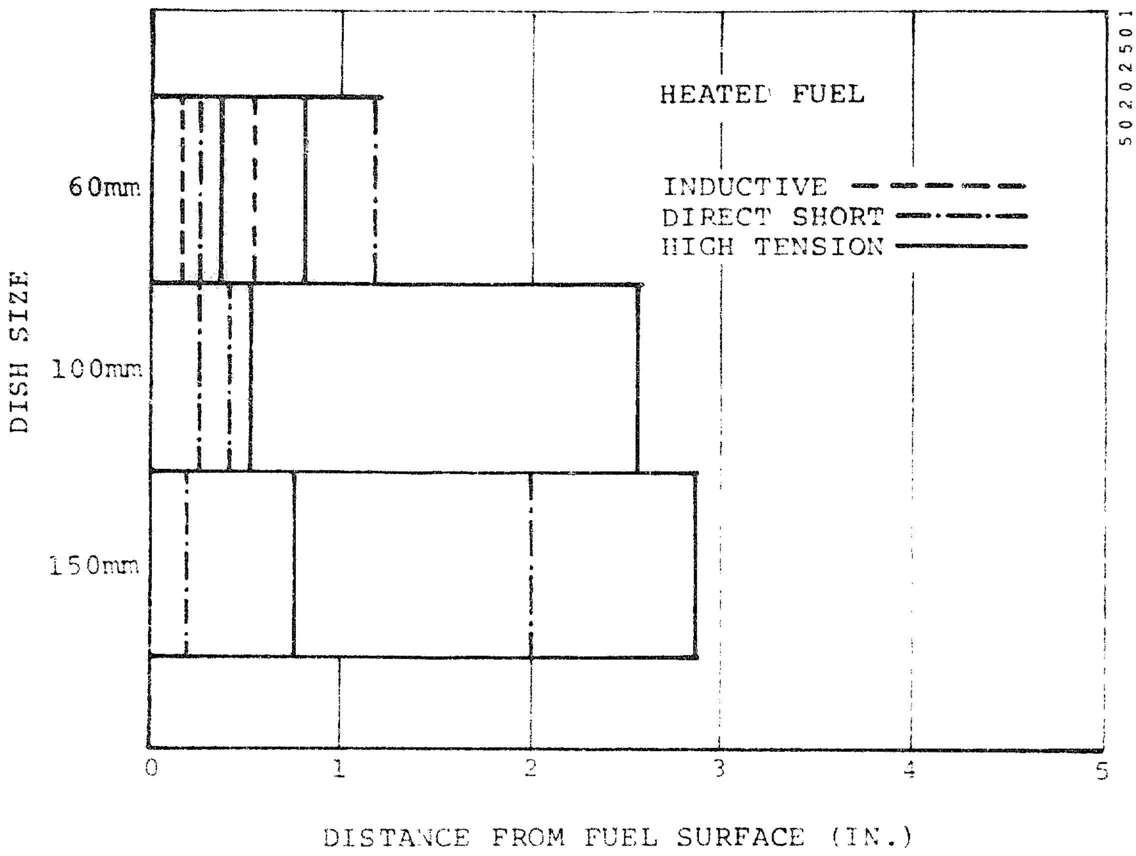
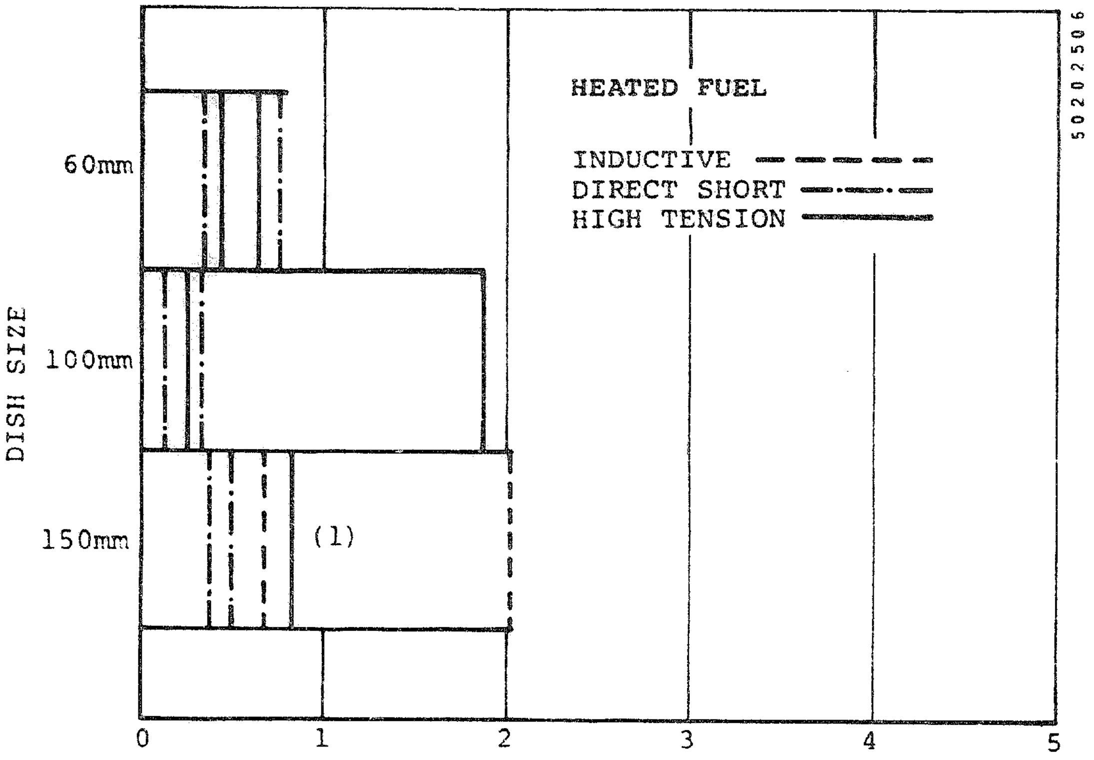


Figure 3-18. Closed Environment Ignition Bands (Hood 6 Inches From Fuel Surface).

Extrapolation of the band widths determined in the laboratory to the real world of an automobile crash cannot be done in a literal sense, and this was not the intent of the laboratory tests. When fuel is spilled under dynamic conditions, a fuel spray is formed containing many pockets of flammable vapors. In addition, the fuel is sprayed over distances ranging up to several feet. Thus it must be assumed that flammable vapors can come in contact with many ignition sources during a crash. The laboratory tests served to define which of these possible ignition sources could, in fact, ignite a crash fire. Those ignition sources igniting fuel under all of the laboratory test conditions can certainly function as prime ignition sources, while those which did not



(1) IGNITION OCCURRED AT SAME POINT FOR BOTH PROBE DIRECTIONS

Figure 3-19. Closed Environment Ignition Bands (Hood 12 Inches From Fuel Surface).

ignite under any of the test conditions can be dismissed as possible ignition sources.

3.6.1.3.2 Broken Headlights. Figure 3-22 shows one of the tests which were run with success using broken headlights as an ignition source. Testing was done only with ambient fuel temperatures since lighted headlamp filaments generally would be exposed to a fuel spray during a rear impact in which the headlight glass of the striking car was broken. No attempt was made to determine a range for this source for the reasons discussed in the previous paragraph. The probe was set in the flammable range where ignition had occurred for the electrical sparks and the light was turned on. Ignition took place in all of the tests. Figure 3-22 shows the headlamp filament still had not broken when the fire

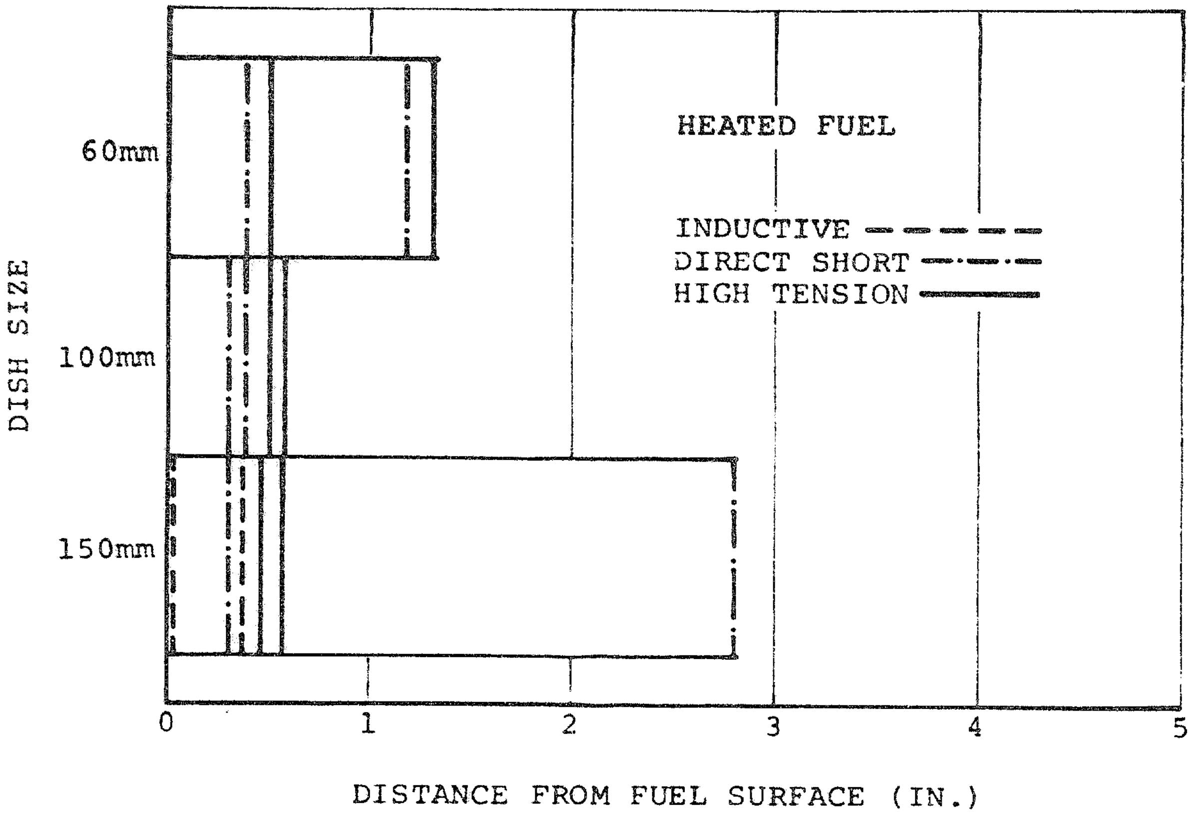
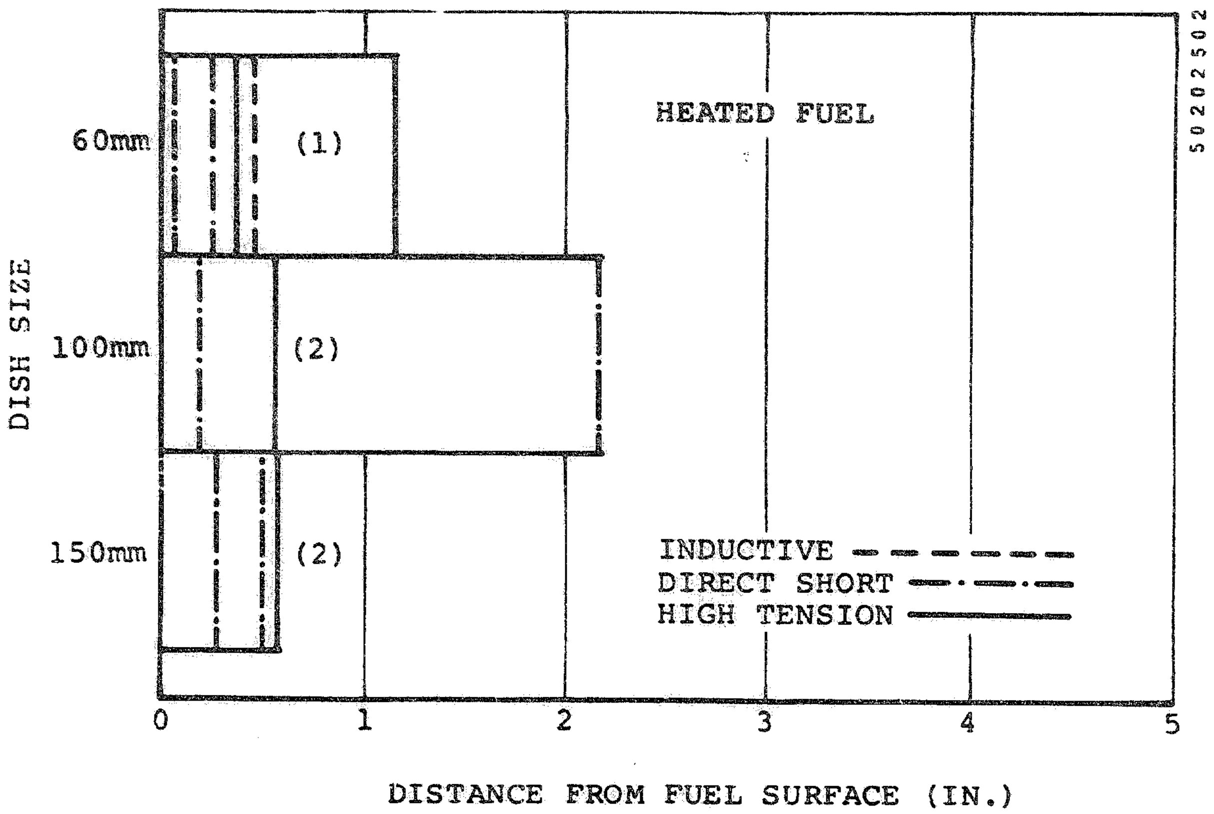


Figure 3-20. Heated Closed Environment Ignition Bands (Hood 6 Inches From Fuel Surface).

started. One headlamp was used for four tests which shows that the filament will last for some time when exposed to the air.

Reference 14 indicates that the method of ignition in this case is not that of a hot surface but of an open flame. When the white hot tungsten wire is exposed to oxygen in the presence of a flammable fuel/air mixture, the filament rapidly oxidizes, bursts into flames, and ignites the mixture. The laboratory tests confirmed this ignition method.

The laboratory tests determined that automobile headlights could easily ignite gasoline if they survived the impact of the vehicle in a crash. This aspect is discussed in Section 3.9.2.



(1) IGNITION ONLY OCCURRED ON MOVING PROBE DOWN

(2) IGNITION OCCURRED AT SAME POINT FOR BOTH PROBE DIRECTIONS

Figure 3-21. Heated Closed Environment Ignition Bands (Hood 12 Inches From Fuel Surface).

3.6.2 Friction Spark Ignition Source

3.6.2.1 Test Equipment and Procedures

The fixture for this test was basically the same structure which was used in the electrical ignition source tests. Figure 3-23 shows the modifications which were made to the fixture. The aluminum rack which moved the electrode into position was modified to hold the friction spark device in position over the fuel dish. Provisions were made to force a 3-inch by 3-inch by 6-inch test specimen of paving concrete against a rotating steel wheel. The wheel was scalloped out and beveled so a high contact pressure could be maintained. The air motor was fed pressure of 150

Figure 3-22. Ignition Test Using Broken Headlight as Ignition Source.

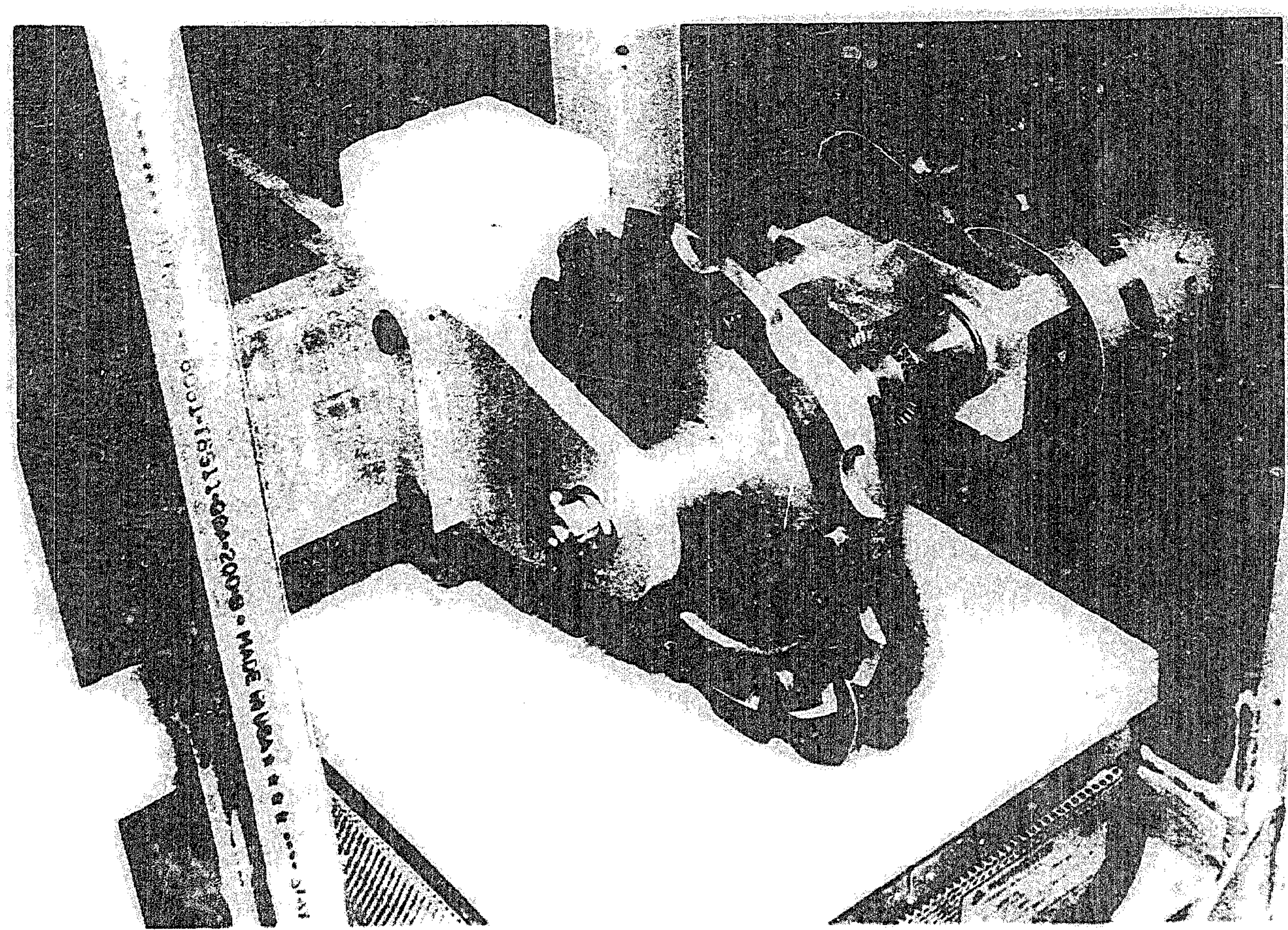


Figure 3-23. Test Apparatus for Friction Spark Ignition Tests.

psi from the shop air supply to assure full output power was available. Friction sparks were generated over the fuel dish.

3.6.2.2 Materials Tested

Paving concrete was considered to be a greater hazard from a spark standpoint than asphalt because of the hard rock content in concrete. A local company that does paving for the state was contacted and a formula for the mix was obtained. This consisted of 51.7 percent rock, 33.7 percent sand, and 14.6 percent cement by weight. The rock content was high enough to obtain good sparking.

The wheel was fabricated from 1020 steel which is similar in composition to the main structural and sheet metal in a car. Construction of wheels from spring steel and cast iron was not undertaken due to material availability problems.

3.6.2.3 Test Results

Figure 3-24 shows one of the tests. Sparking was maintained from 10 to 20 seconds. Ignition did not occur during any of the tests. However, these results cannot be considered conclusive. The moving air generated by the rotating wheel caused considerable disturbance of the flammable vapors above the fuel dish. However, the laboratory tests did show that this ignition source is less hazardous than some of the electrical sources.

Friction spark tests have been conducted outside the laboratory by other investigators. Fiat conducted two types of such tests (Reference 13). The first consisted of dragging a heavily damaged car body over macadam and concrete while gasoline was sprayed around the sparking areas. The second test series used a specially designed dolly which carried pieces of sheet metal of varying thickness in contact with macadam and concrete while gasoline was dripped in different areas in front of and behind the test specimen. No sparking occurred up to 20 km/hr regardless of contact pressure. Ignition occurred in only 10 percent of the tests above this speed.

Friction spark ignition source testing was [illegible] conducted at the Lewis Flight Propulsion Laboratory to determine the friction spark hazards of certain aircraft metals under simulated crash conditions. Although this study does not apply directly to automobiles, many items show a correlation. Tests were performed by inserting a test specimen in a fixture which was pulled over a concrete runway by a truck. The contact pressure on the specimen was controllable as was the test velocity and type of fuel spray. Igniters were provided to determine that a flammable mixture did exist. Five types of materials were tested: aluminum, titanium, magnesium alloy, 4130 steel, and 347 stainless steel. Aluminum,

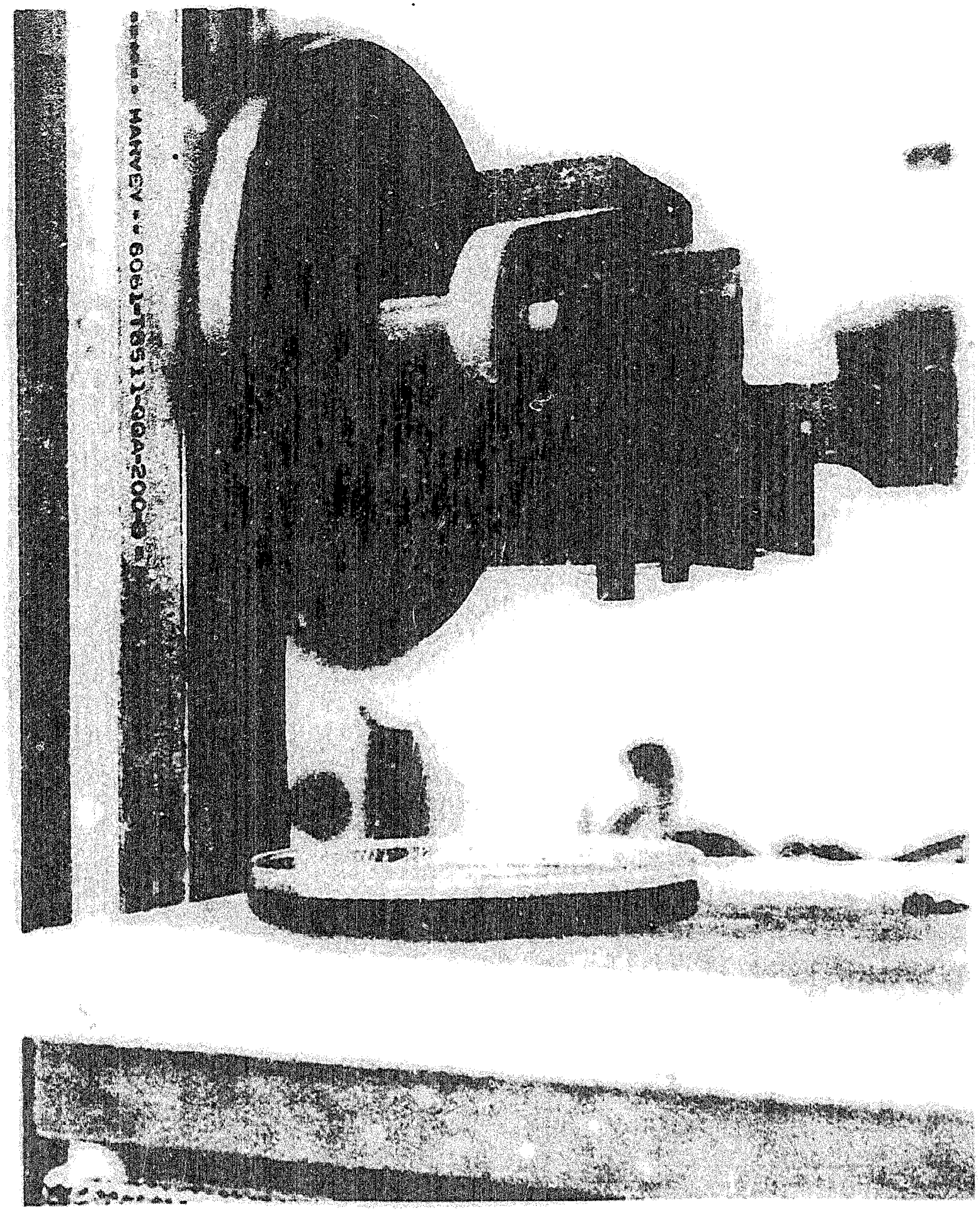


Figure 3-24. Friction Spark Ignition Source Test.

titanium, titanium alloy, and magnesium alloy are not of interest in the automotive field as they are not used in production vehicle structures. The steel materials which were tested, 347 and 4130, are of interest since their composition is closer to the 1020 steel used in automobiles. (The 4130 should exhibit the closest characteristics to the 1020.) At 20 mph and a pressure of 20 psi, it took 12 seconds for ignition of 100/120 gasoline to occur. The shortest slide time resulting in ignition was 8 seconds with 145 psi pressure and 20-mph slide speed. Tests with 347 steel showed somewhat longer times and required higher pressures (Reference 18).

3.6.3 Gasoline Autoignition

3.6.3.1 Test Equipment and Procedures

This test was conducted with two different hot surface sources. A strip heater was used for the first series of tests. The heater was fastened to the inside of the pan for the closed environment electrical ignition source tests. This provided a semiclosed environment similar to under-the-hood conditions in an automobile. The tests were conducted at temperatures from 300° to 1,000°F in 50° increments. At each temperature 10 drops of gasoline were placed on the strip heater and the temperature was maintained for 60 seconds to assure an adequate delay time was allowed.

A second test series was conducted using a hot plate as the hot surface. Test temperatures from 300° to 700°F were utilized in 50° increments. Ten ml of fuel was poured on the hot plate and retained there by an open metal cylinder placed on the hot plate. A delay of 60 seconds was observed prior to going on to the next test.

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18. Campbell, John A., Appraisal of the Hazards of Friction Spark Ignition of Aircraft Fires, NACA TN 4024, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, May 1957.

A third test series was performed with the hot plate heated to 700°F. The inverted pan with the heater strip inside was then placed over the hot plate, the strip was heated to 1,050°F and 20 ml of fuel was dropped through the opening in the pan onto the hot plate.

3.6.3.2 Test Results

Test results in all cases were negative with no ignition at any temperature level or time delay. The fuel evaporated very rapidly in all of the tests, and it is probable that the rapid evaporation precluded sufficient heating within the liquid fuel to cause it to autoignite. The test results are consistent with the data presented in Table 3-2 which shows that the autoignition temperature rises as the volume of the fuel decreases and the surface area to volume ratio increases. The autoignition temperature of gasoline under the laboratory test conditions could well be near 1,000°F.

The laboratory tests simulated the majority of spilled fuel/hot surface conditions found during an automobile impact. The fuel is generally sprayed or spilled on a hot surface where it either evaporates or runs off. It is unlikely that a sufficient quantity of fuel would be trapped on the surface of a hot component long enough for autoignition to occur.

3.7 DEFINITION OF HAZARDOUS IGNITION SOURCES

3.7.1 Electrical Sources

Based on the laboratory testing, electrical sources appear to be the most hazardous from the standpoint of possible ignition. However, it was determined that not all electrical components are hazardous. A broken headlamp wire is no hazard unless the hot lead of the headlamp circuit contacts the vehicle ground resulting in a direct short. This same situation also exists for taillight and brakelight wiring which would be vulnerable in a rear impact. Sparking which could result from the breaker in a distributor does not pose a threat even with the coil lead open.

A direct battery short is an extremely effective ignition source and should be considered one of the most dangerous. The battery is often located in an area of the vehicle where sheet metal is displaced in a crash and can come in direct contact with the positive battery terminal. A direct short can also occur in low-energy circuits when the hot lead is broken and shorted to ground. Test results show this source will ignite fuel in all cases when the fuel vapor is within flammable limits.

A broken spark plug wire would also be a very effective ignition source; however, it is unlikely that it would be sheared or pulled loose in a minor collision wherein the engine is still running. Cracked leads could also allow sparking if they were to come in contact with a grounded piece of metal while the engine was running.

The extra-current inductive spark produced when the wire from the air conditioner compressor is broken is also capable of igniting flammable fuel vapors under most conditions and must be considered an ignition source hazard. However, the wires are generally fairly well protected by their location and do not present as great a hazard as a direct battery short.

3.7.2 Vehicle Headlights

Vehicle headlights present a very definite ignition hazard. Under test conditions they ignited gasoline in all the same ranges as a direct battery short. Contrary to popular belief, they are also not necessarily destroyed in a vehicle impact. Examination of a dozen cars previously crashed into a fixed barrier at 30 mph showed that approximately 25 percent of the headlights that had been broken still had intact filaments.

Headlamps may continue to burn for 30 seconds or more in open air. They are probably one of the best ignition souces available in a rear impact. As previously noted, a higher rate of fire accidents occurs after dark than would be justified by the total after-dark fatality increase of all accidents.

Therefore, when a flammable gasoline mixture is available, the headlamp must be considered a very definite source of ignition.

3.7.3 Friction Sparks

Friction sparks do not appear to pose as significant a fire threat although they are undoubtedly responsible for some crash fires. The laboratory testing was unsuccessful in obtaining ignition and testing by another company with full-scale vehicles could accomplish ignition in only 10 percent of the cases. The required delay time to initiate ignition is usually not available in an automobile crash. When vehicle movement has decreased below 10 mph, virtually no sparking occurs. Vehicle speed generally drops very rapidly following an accident and does not provide the minimum 5 to 10 seconds at higher speeds required for ignition. It is fortunate that friction sparks do not represent a large hazard for there is little that can realistically be done to eliminate them in the near future. If they did pose a high threat, virtually all external metal on an automobile would have to be protected from surface friction in the event of suspension or wheel failure or a rollover.

3.7.4 Autoignition

The heated surfaces in a vehicle represent a low ignition hazard in a primary mode. Laboratory testing was unsuccessful in obtaining ignition, and tests by other companies indicated very high temperatures (800°-1,000°F) were necessary for autoignition under the conditions experienced during an automobile crash.

Certain vehicles with catalytic converters could pose a slight hazard since temperatures on these units may reach 950°F on some types. However, temperatures of 950°F, which were recorded for converters, were at 80 mph rather than the 55-mph speed limit. Oil and transmission fluid can also pose a hazard with the converter since they can ignite at a lower temperature than gasoline and thus serve as an ignition source for spilled fuel.

The heated surfaces represent a hazard in a secondary mode since they can provide vaporized gasoline to areas where effective electrical ignition sources exist. A heated surface such as an exhaust manifold is capable of vaporizing large quantities of gasoline before its energy is expended.

The heated surface would be almost impossible to eliminate or insulate in an automobile; however, the fuel system may be routed to lessen spilling of gasoline on the exhaust system during or after an impact.

4.0 BASELINE VEHICLE TESTS

A series of four crash tests was conducted during this program to establish baseline conditions for crash fires: a barrier test, two front-to-rear impact tests, and a rollover test. These tests provided spilled fuel and ignition sources in the form of open high-voltage sparks at impact to ensure that a fire would result. The same conditions which were used for fire in these crashes were used in the subsequent demonstration tests to prove that the countermeasures did indeed prevent fires.

The above conditions were required for undeniable proof of the countermeasures effectiveness since only a small percent of automobile crashes result in fire. Without these provisions there could be no assurance that an electrical spark ignition scurce and flammable fuel vapors would both exist at the same location in the same precise moment of time. By assuring that a fire would occur without the countermeasures, one could also assure that the countermeasures were effective during the demonstration tests if a fire did not occur.

The baseline test vehicles were also evaluated in regard to structural damage and fuel and electrical system damage. This information was utilized in the selection and installation of appropriate countermeasures for the subsequent demonstration tests.

4.1 TEST EQUIPMENT

The baseline test series required the design of specific test equipment to produce the ignition sources and spilled fuel required for the various tests. The following equipment was fabricated for the tests; spark igniter package, fuel spray system, fuel tank ram, bumper plates, and a barrier fuel pan.

The spark igniter package was developed to produce open sparks in 6 locations on the test vehicle after impact. The spark igniter package basically consisted of a 6-volt battery, Ford ignition coil, and distributor, as shown in Figure 4-1.

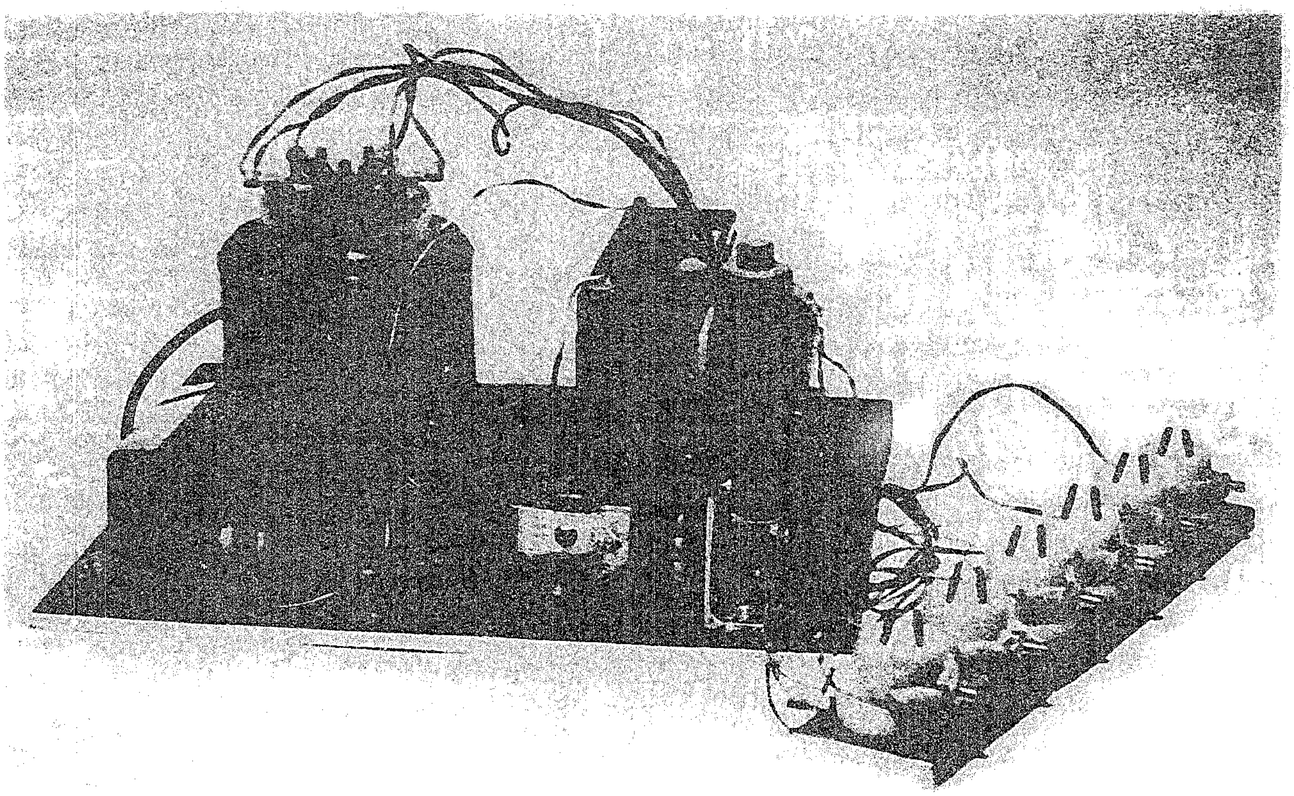

Figure 4-1. Spark Igniter Package.

The switch that activated the spark igniter package was an inertia switch that required approximately 5Gs of deceleration to close. The time delay from the moment of impact to activation of the igniters was approximately 75 msec. This package was mounted in the vehicle in all four tests.

The fuel spray system consisted of a 2-gallon pressure tank and a solenoid valve (Figure 4-2) that provided fuel to two nozzles mounted on the firewall in the engine compartment. The fuel spray solenoid was connected to the battery and impact switch of the spark igniter package so that the spray would start after impact when the igniters were activated. The fuel spray was used on the rollover test and the front-to-rear test where the igniters were located inside the engine compartment to ensure that flammable vapors would be present around the igniters.

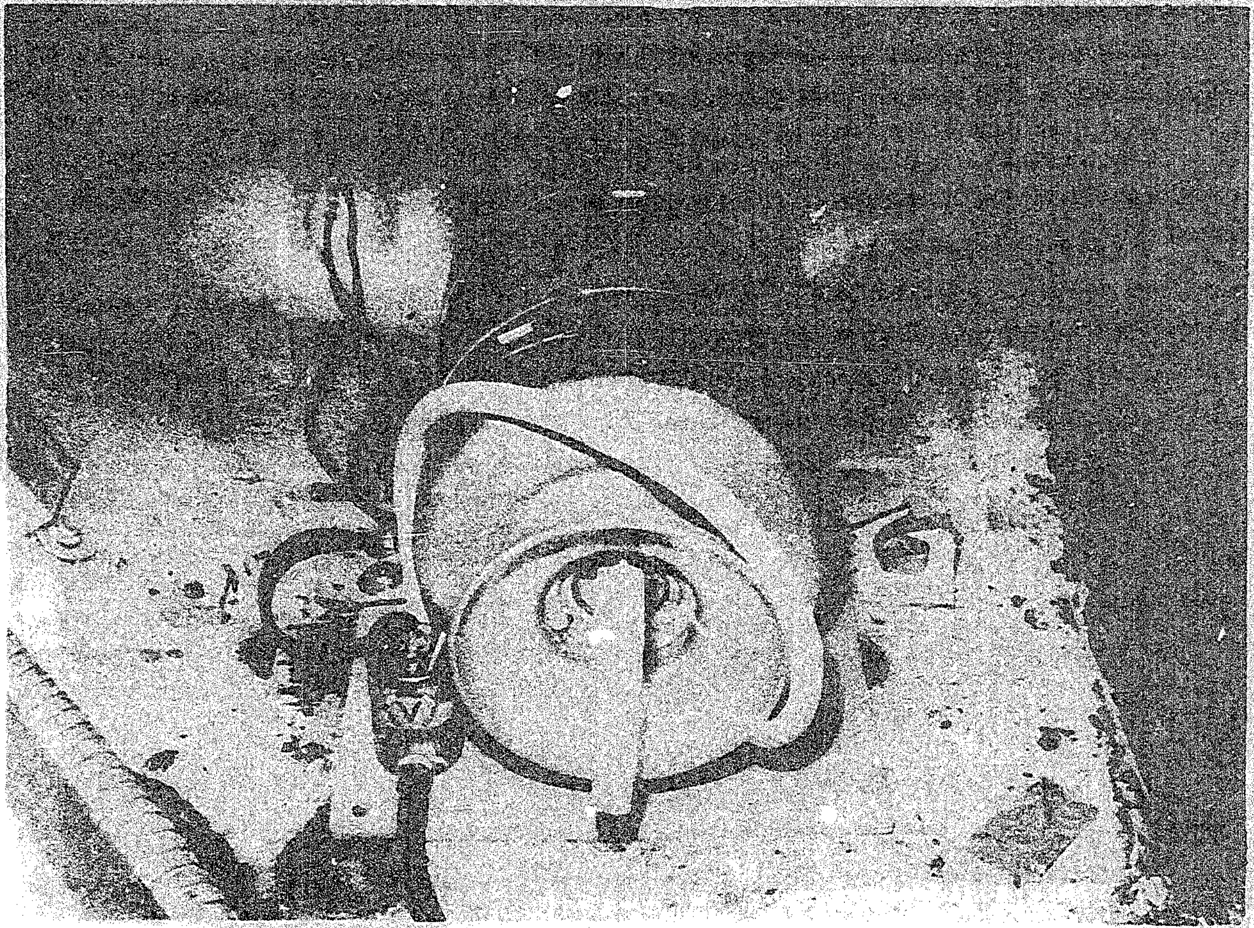

Figure 4-2. Fuel Spray System.

A fuel tank ram was designed for use in both front-to-rear tests to provide the worst condition for intrusion into the existing gas tank area. A sleeve that contained a stroking rod bearing a 3-1/2-inch square metal plate was mounted to the rear bumper of the struck vehicle (Figure 4-3). The rod would be pushed forward by the striking car into the struck car's gas tank.

Two bumper plates were also installed on the struck vehicle's rear bumper to prevent the striking car from overriding the rear of the struck car (Figure 4-3). These plates provided a means of obtaining more repeatable tests and maximizing the rear end crush of the struck car.

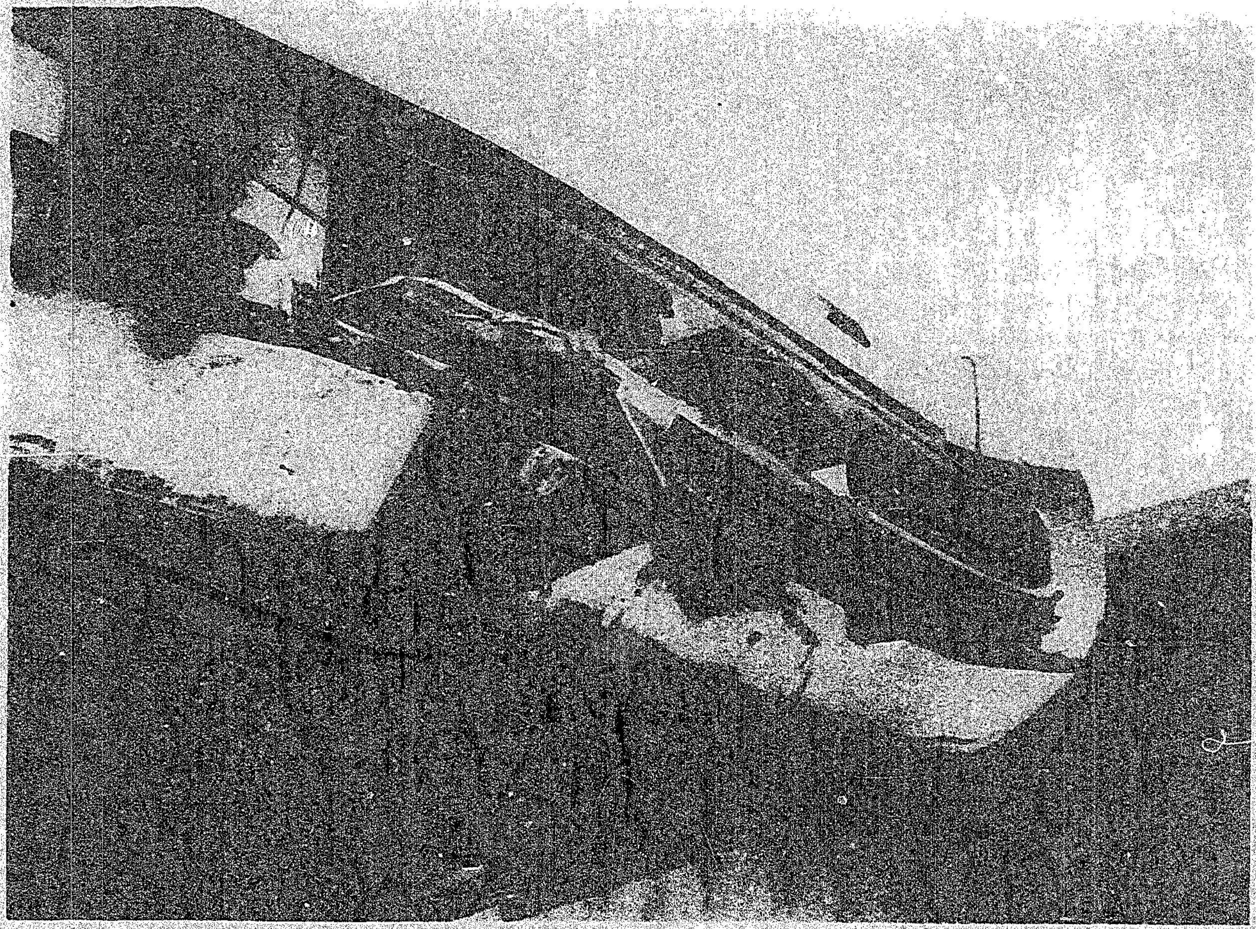

Figure 4-3. Fuel Tank Ram and Bumper Plates.

A shallow fuel pan was constructed to retain approximately 10 gallons of pooled fuel at the face of the barrier. The sheet metal pan was mounted to plywood and anchored to the grating in front of the barrier. The test vehicle would enter the pan just prior to impact with the barrier and remain there after impact so that ignition might occur from the igniters mounted under the test vehicle.

All of the test vehicles were 1971 Plymouth Fury sedans. Older vehicles were not used because fuel evaporative emission control systems were not required on all automobiles until the 1971 model year. Five vehicles were obtained for the test series. The striking car in the first front-to-rear test was not damaged aft of the A pillar during the test. Therefore, it was used as the struck car in the second front-to-rear test.

There was no electronic instrumentation on board the vehicles because of its susceptibility to fire damage. However, data were recorded by means of high-speed motion pictures that were time coordinated to provide event histories.

4.2 TEST CONDUCT AND RESULTS

4.2.1 Barrier Test

The test vehicle was equipped with the spark igniter package and the spark sources mounted under the car as illustrated in Figure 4-4. The fuel system was drained completely and the fuel tank was filled with water. An auxiliary fuel tank was installed at the rear of the vehicle to provide sufficient fuel for engine operation throughout impact.

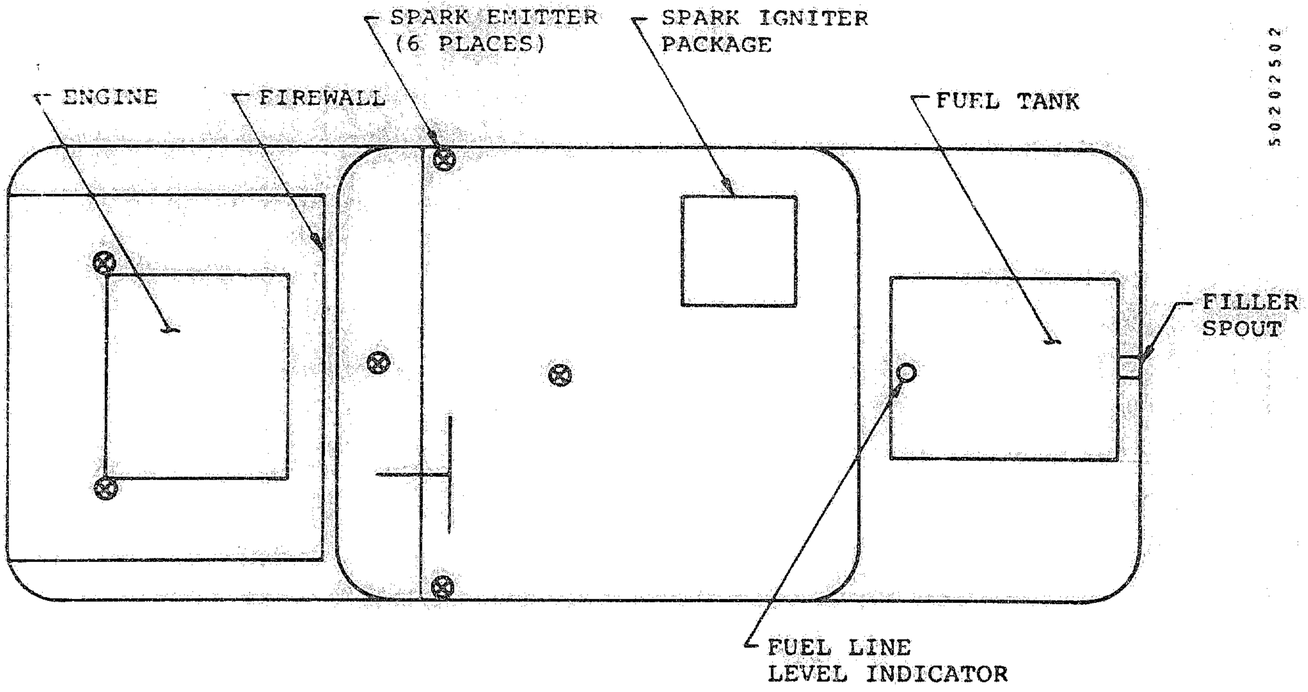

Figure 4-4. Spark Igniter Configuration for Barrier Test.

The engine was started and run for 15 minutes just prior to the test to permit the engine to reach normal operating temperature. When the vehicle was ready, 7 gallons of fuel were added to the barrier pan. The test vehicle was then towed into the barrier with its engine still running. The impact velocity was 30.44 mph.

Flames were first seen from behind the left front tire 1.35 seconds after impact. The flames spread throughout the fuel mist at a rate of 18 feet/second, resulting in the fire shown in Figure 4-5. The fire was extinguished soon after impact.

Figure 4-5. Baseline Barrier Test Results.

Damage to the test vehicle is shown in Figure 4-6. The maximum dynamic crush experienced by the vehicle was 26 inches. This resulted in electrical system damage consisting of broken headlights (3 out of 4), severed headlight and parking light wires, and minor damage to the battery. Buckled sheet metal was forced into contact with the positive battery terminal. The fuel system was not damaged.

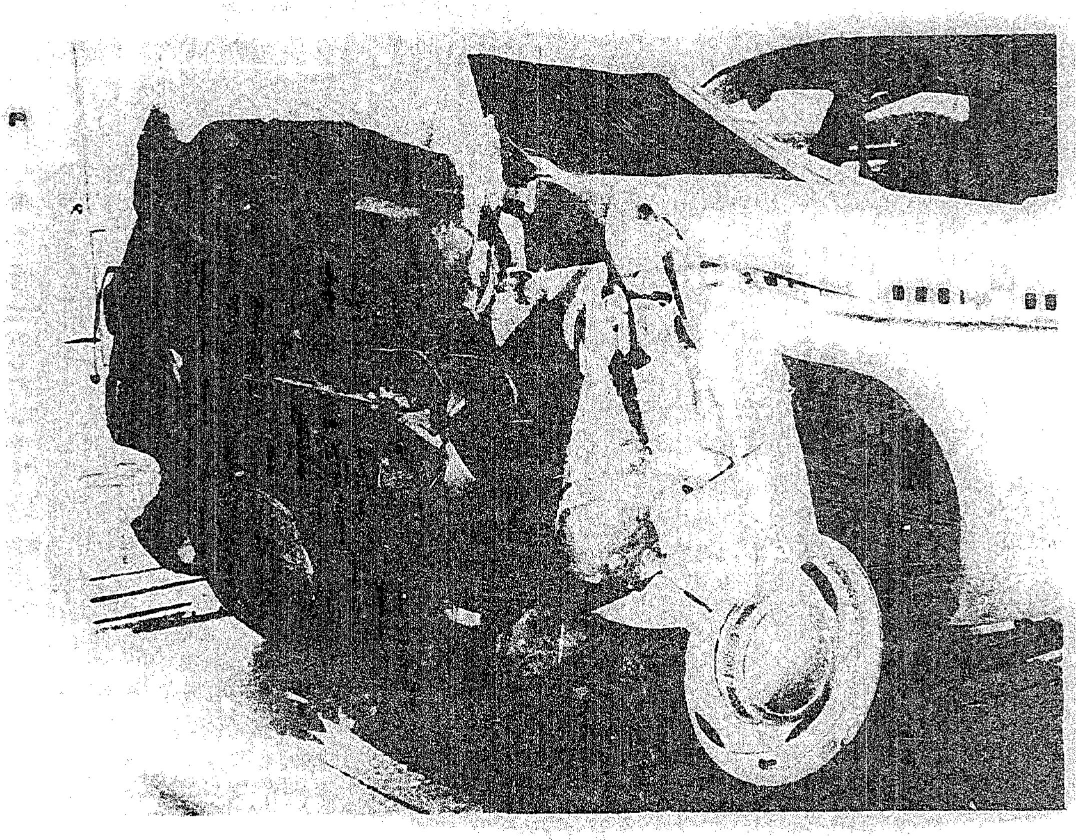

Figure 4-6. Damage to Baseline Barrier Test Vehicle.

4.2.2 Spilled Fuel Front-to-Rear Test

The first front-to-rear test was a 60-mph impact evaluating the struck vehicle's fuel system. The struck vehicle was equipped with the spark igniter package and the fuel tank ram as illustrated in Figure 4-7. Four igniters were mounted under the vehicle near the fuel tank and two igniters were trailed along

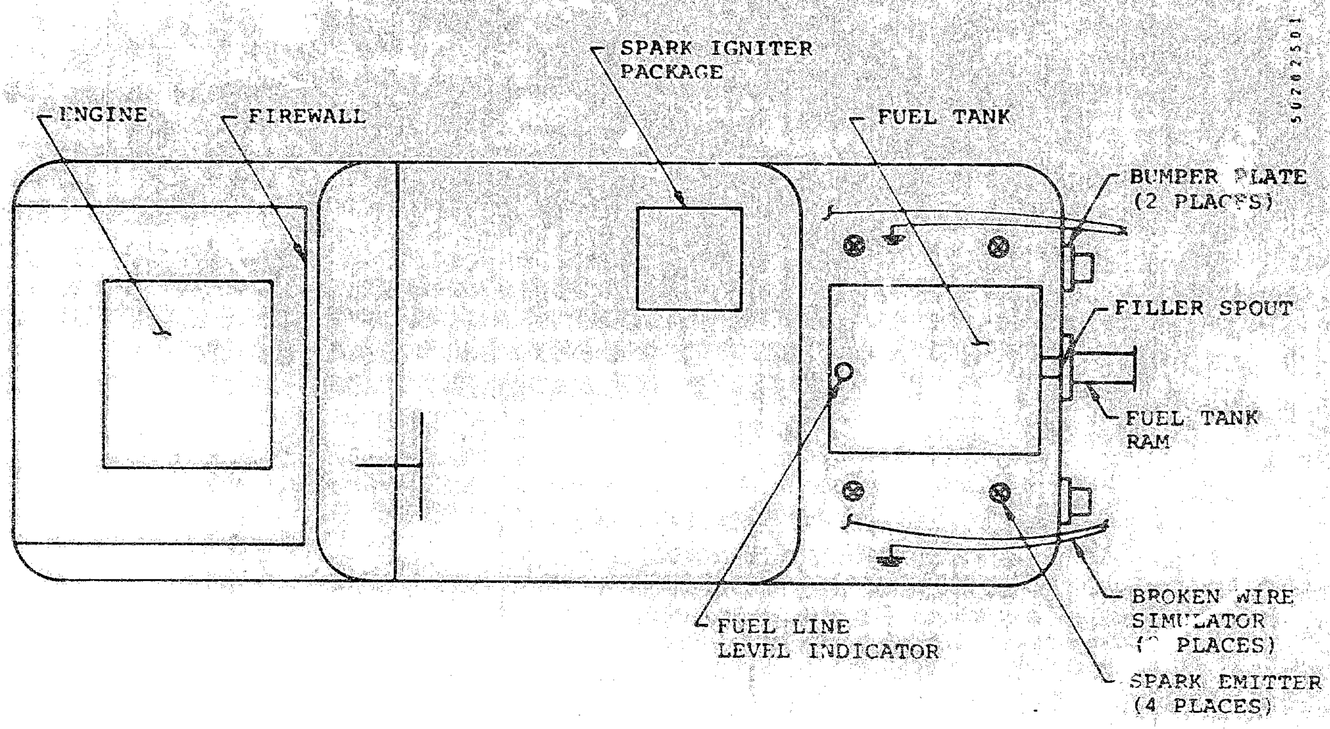

Figure 4-7. Struck Vehicle Spark Igniter Configuration for Spilled Fuel Front-to-Rear Test.

the ground to simulate broken wires. The fuel tank was filled to 90 percent of its capacity with gasoline.

The striking car was equipped with an onboard abort system which applied the vehicle's brakes 0.5 second after impact. No other modifications were made to this vehicle.

The impact velocity of the striking vehicle was 59.28 mph. Spilled fuel was evident 96 msec after impact with fire visible in 390 msec. Again the flames spread rapidly through the fuel mist and the momentum of the vehicles carried the striking car into the flames, completely engulfing it within three-quarters of a second as shown in Figure 4-8. The flaming fuel followed the vehicles from the impact point to their stopping place 120 feet beyond impact. As the vehicles stopped, the struck car was completely enveloped in flames as shown in Figure 4-9. Burning fuel stretched from the impact point to the vehicles' final resting place.

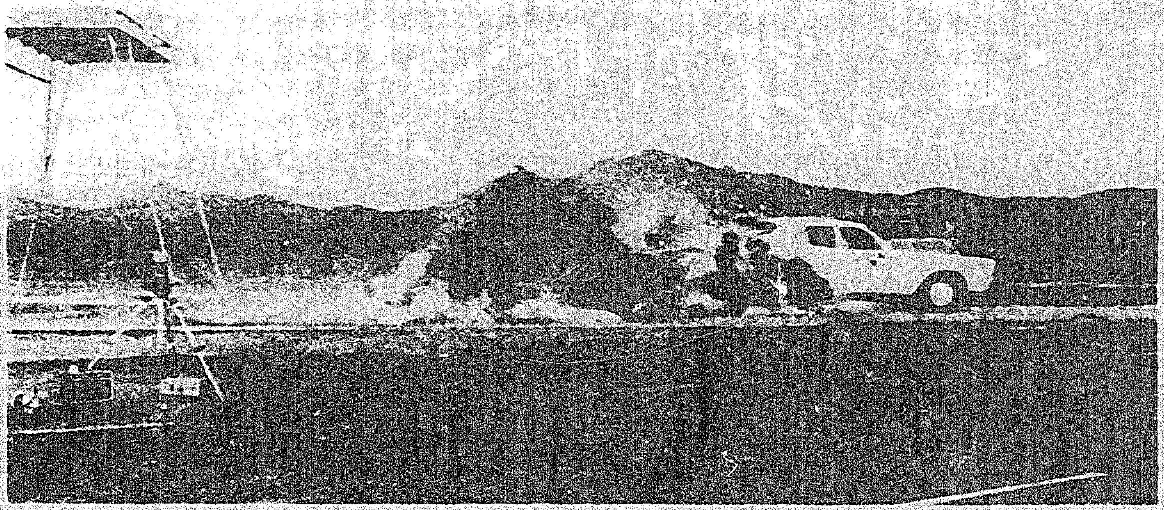

Figure 4-8. Initial Fire Occurring During Front-to-Rear Impact.

Figure 4-9. Fire When Front-to-Rear Impact Vehicles Stopped.

Damage to the struck car is shown in Figures 4-10 through 4-12. The total dynamic crush measured 48 inches, resulting in the rear end of the vehicle being crushed up to the rear tire. Some deformation was also visible in the kick-up area over the rear axle. The fuel tank was crushed between the rear bumper and differential and the filler spout was pulled out of the tank. However, the majority of the spilled fuel escaped from the tank through a separation of the left side seam and through a tear in the rear of the tank.

Although the fire was quickly extinguished by a foam equipped fire truck stationed alongside the impact area, there was extensive fire damage inside the struck vehicle as shown in Figure 4-13. The headlining was completely burned away and the tops of both front seats and both rear doors were scorched and blistered. The fire pattern indicated that the flames entered the vehicle through the shattered backlight and ignited the headlining.

Damage to the striking vehicle was confined to the area forward of the A pillars (Figure 4-10) and was not as severe as that experienced by the barrier test vehicle due to the softness of the struck vehicle's rear structure. Electrical system damage consisted of broken headlights and severed light wires. The battery was not damaged. Although the exterior paint was scorched and blistered, there was no fire damage inside the vehicle.

4.2.3 Ignition Sources Front-to-Rear Test

The second 60-mph front-to-rear impact was conducted using the ignition sources on the striking car. The struck vehicle was equipped with a fuel tank ram (as in the first front-to-rear test), and the fuel tank was filled to 90 percent of its capacity with gasoline. The striking vehicle was equipped with the spark igniter package and fuel spray system in the engine compartment as illustrated in Figure 4-14. The fuel tank was drained and an auxiliary tank was mounted at the rear of the striking vehicle to supply fuel for engine operation during the test. The engine

Figure 4-10. Post-test View of Vehicles,
Front-to-Rear Test 1.

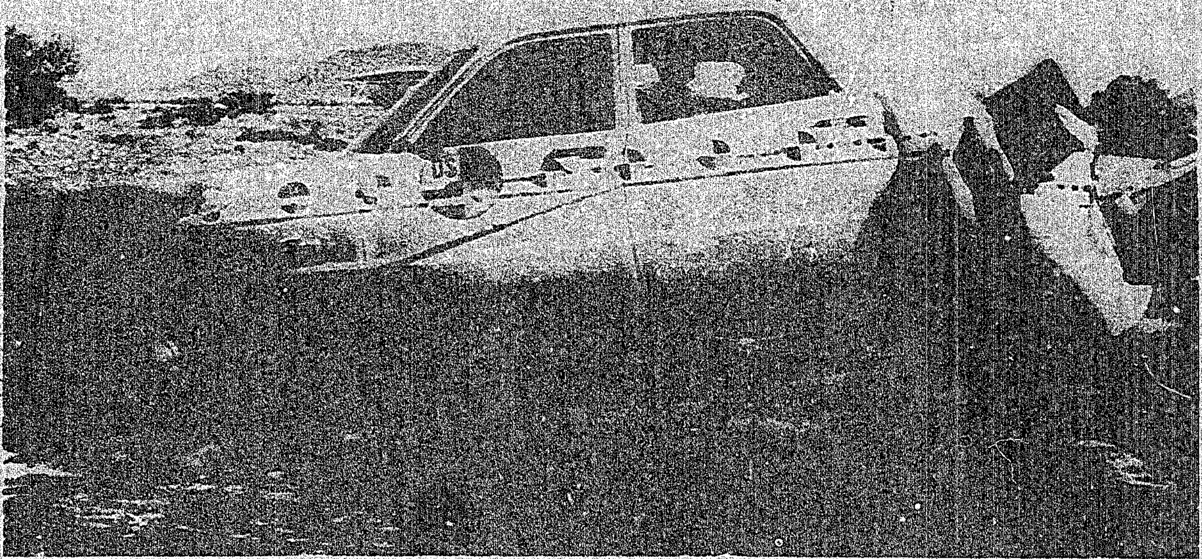

Figure 4-11. Post-test Side View of Struck
Car, Front-to-Rear Test 1.

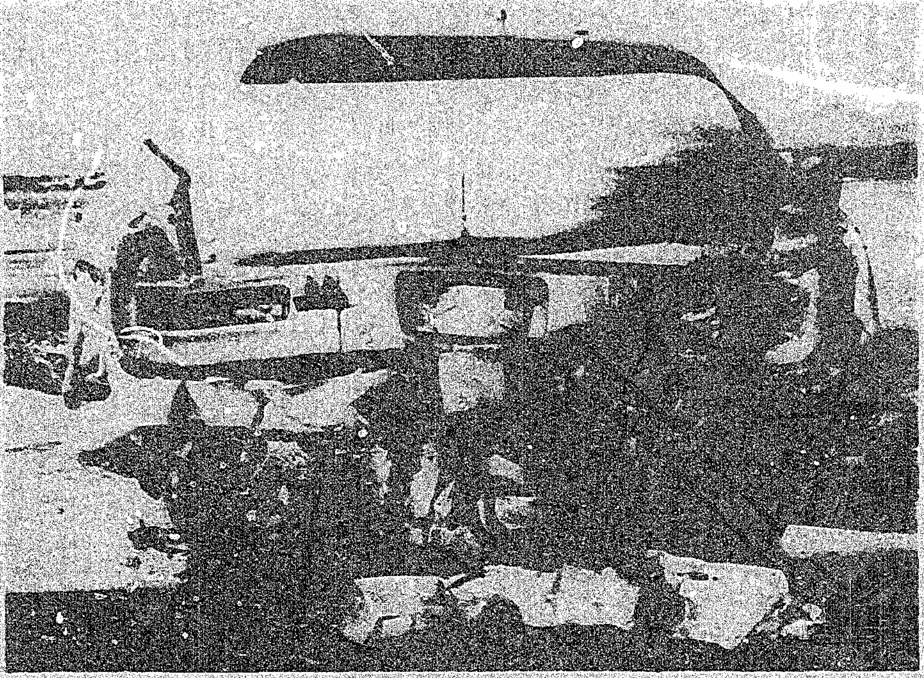

Figure 4-12. Post-test Rear View of Struck Car, Front-to-Rear Test 1.

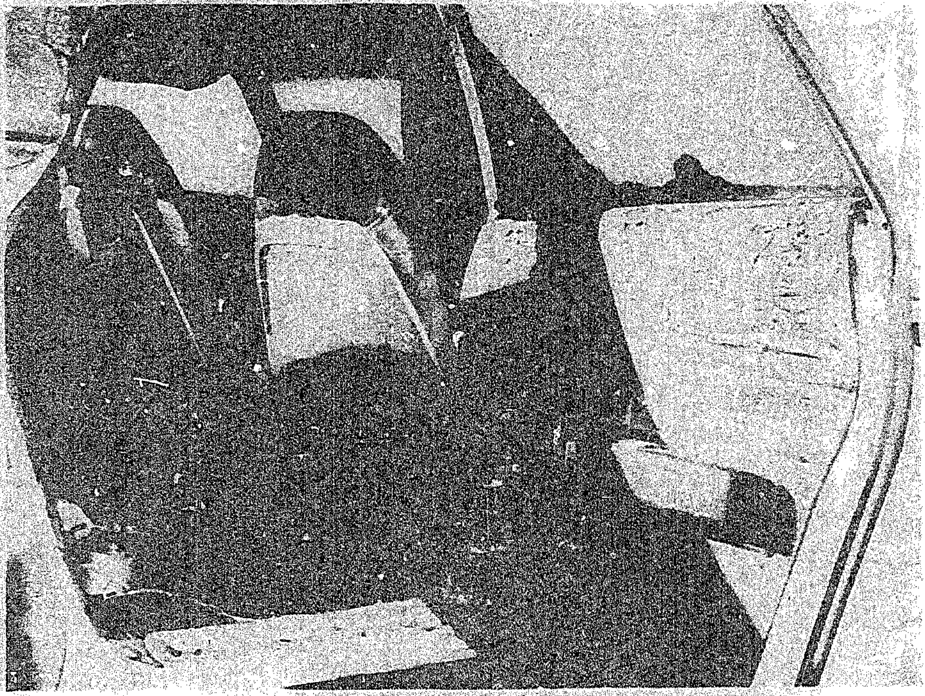

Figure 4-13. Fire Damage Inside Struck Vehicle.

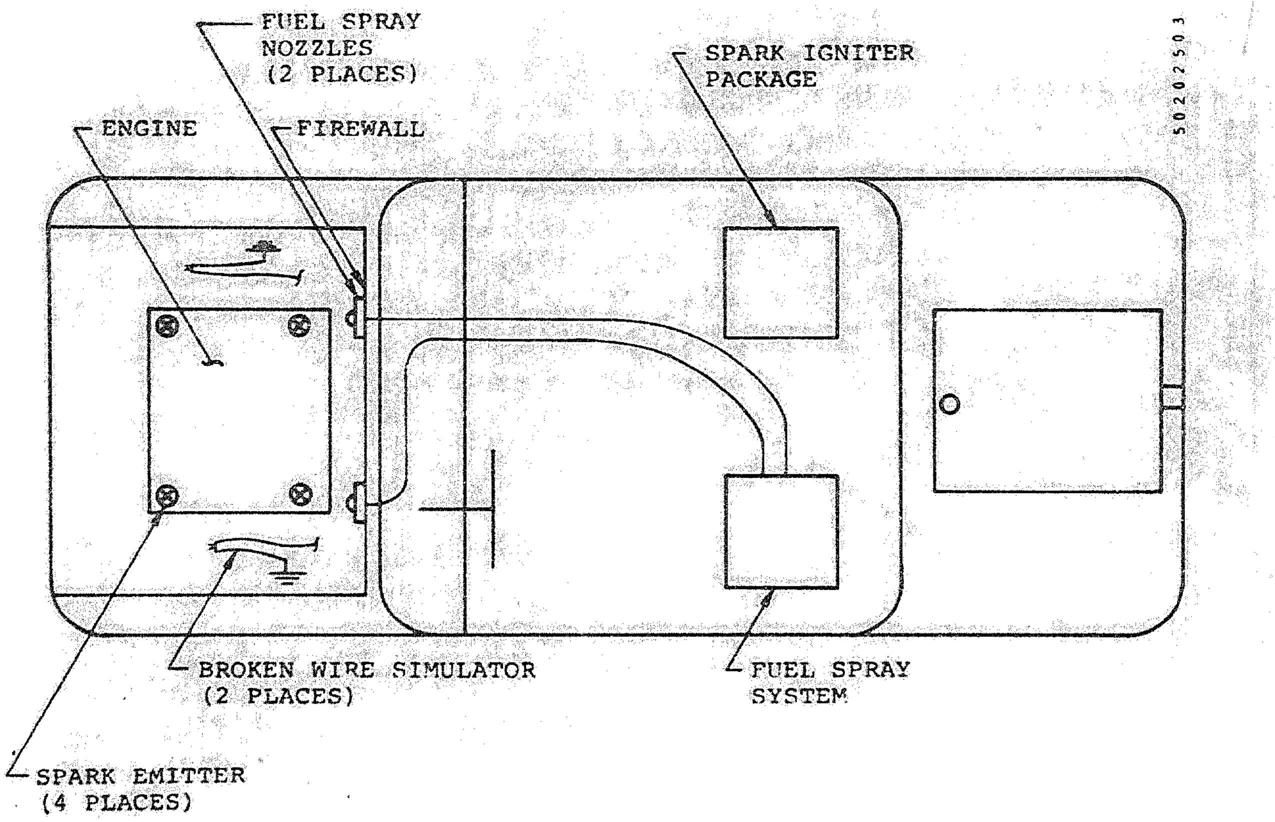

Figure 4-14. Striking Vehicle Spark Igniter and Fuel Spray Configuration for Ignition Sources Front-to-Rear Test.

was started and allowed to idle for 10 minutes before the test so that operating temperatures would be reached. The engine was running at impact.

The striking car struck the rear of the stationary car at 61.67 mph. The results were nearly identical to those of the first front-to-rear test. Fuel from the struck car's gasoline tank was visible 48 msec after impact and the first flames were evident in 260 msec. Again a huge fireball engulfed the striking vehicle and the flames followed the cars until they came to rest as shown in Figure 4-15.

The damage to both vehicles (shown in Figure 4-16) was very similar to that incurred during the first front-to-rear test. However, there was no fire damage inside either one of the

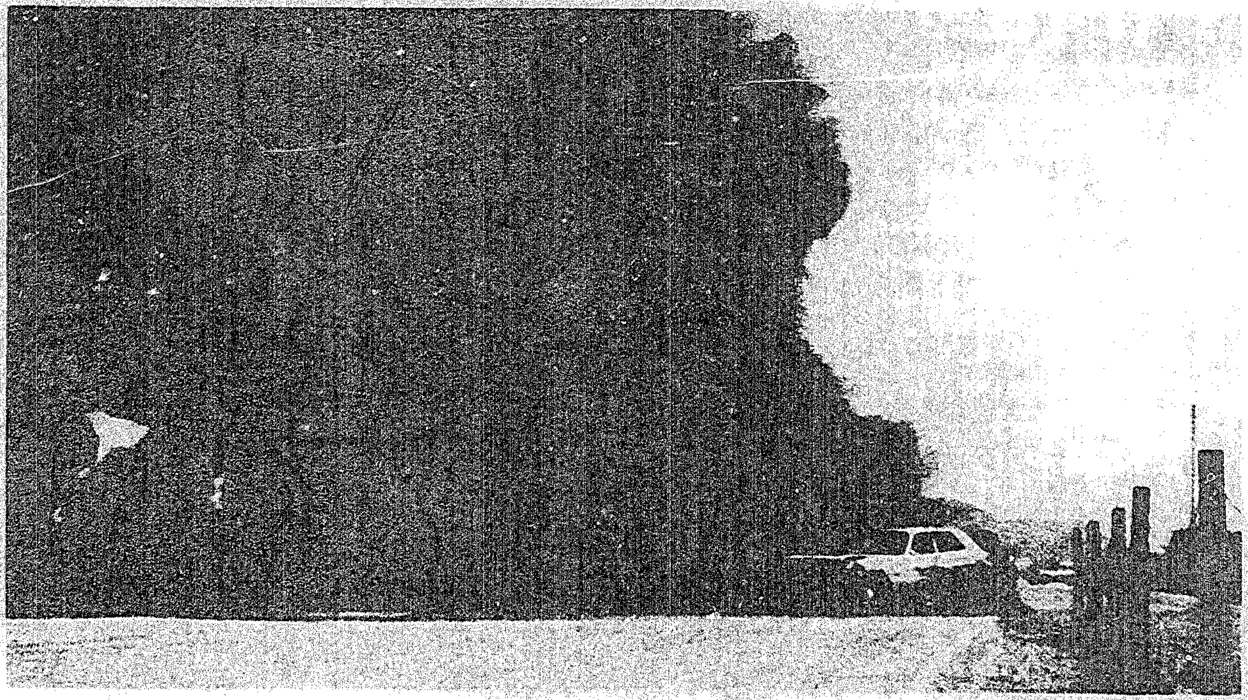

Figure 4-15. Fire as Vehicles Stopped Following Front-to-Rear Test 2.

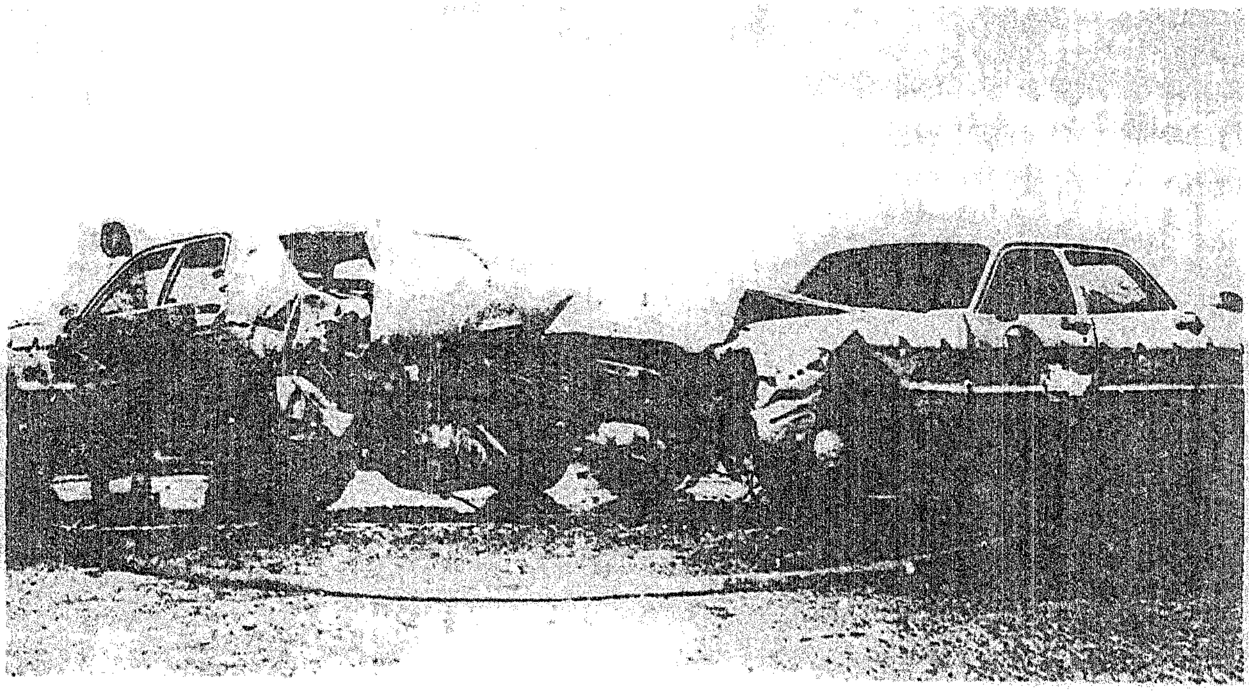

Figure 4-16. Post-test View of Vehicles, Front-to-Rear Test 2.

vehicles as there was in the struck car of the first test. This was due to the different vehicle dynamics and final resting positions of the vehicles during the two tests. In comparing Figures 4-9 and 4-15, it can be seen that the struck car in the first test came to rest in the flames while the struck vehicle in the second test came to rest at the farthest edge of the burning fuel.

4.2.4 Rollover Test

The rollover test was a combination spilled fuel and ignition sources test. The spark igniter package and fuel spray system were installed as illustrated in Figure 4-17. The fuel spray and three igniters were installed in the engine compartment and the other three igniters were mounted in the fuel tank area. The fuel tank was filled to 90 percent of its capacity with gasoline, and the carburetor and fuel lines contained their normal amount of fuel. The test vehicle mounted on the rollover dolly is shown in Figure 4-18. When the vehicle was ready for test, the dolly was accelerated to the test speed and was released just prior to impact with the honeycomb snubbers. The impact velocity of the dolly was 30.62 mph.

The car landed on its right wheels and skidded approximately 6 feet on its tires before it started to roll. It then rolled onto its top and slid approximately 100 feet before it stopped. The maximum roll angle was 226 degrees. The post-test position of the car is shown in Figure 4-19.

Fire was not immediately evident from a distance; however, the engine compartment was on fire. The fire was difficult to extinguish because of the interference of the engine and frame structure. It could not be determined whether the fire was started by the fuel spilled from the carburetor or from the fuel spray.

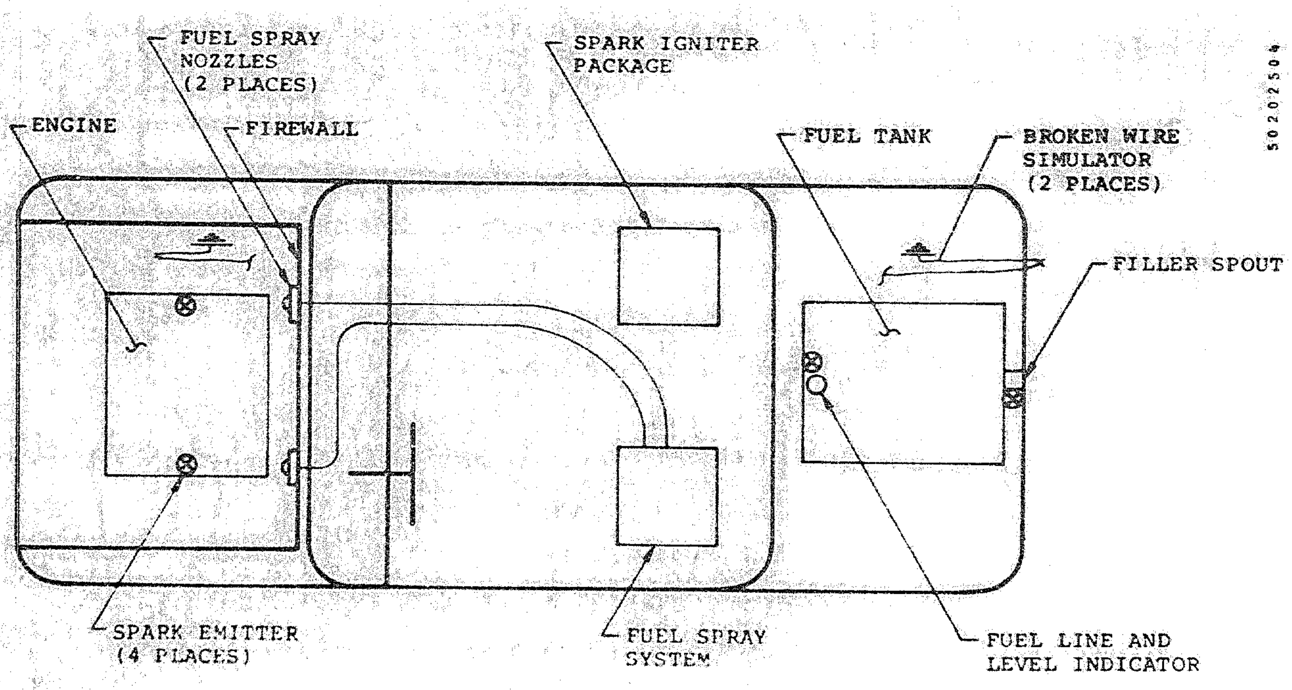

Figure 4-17. Rollover Test Vehicle Igniter and Fuel Spray Configuration.

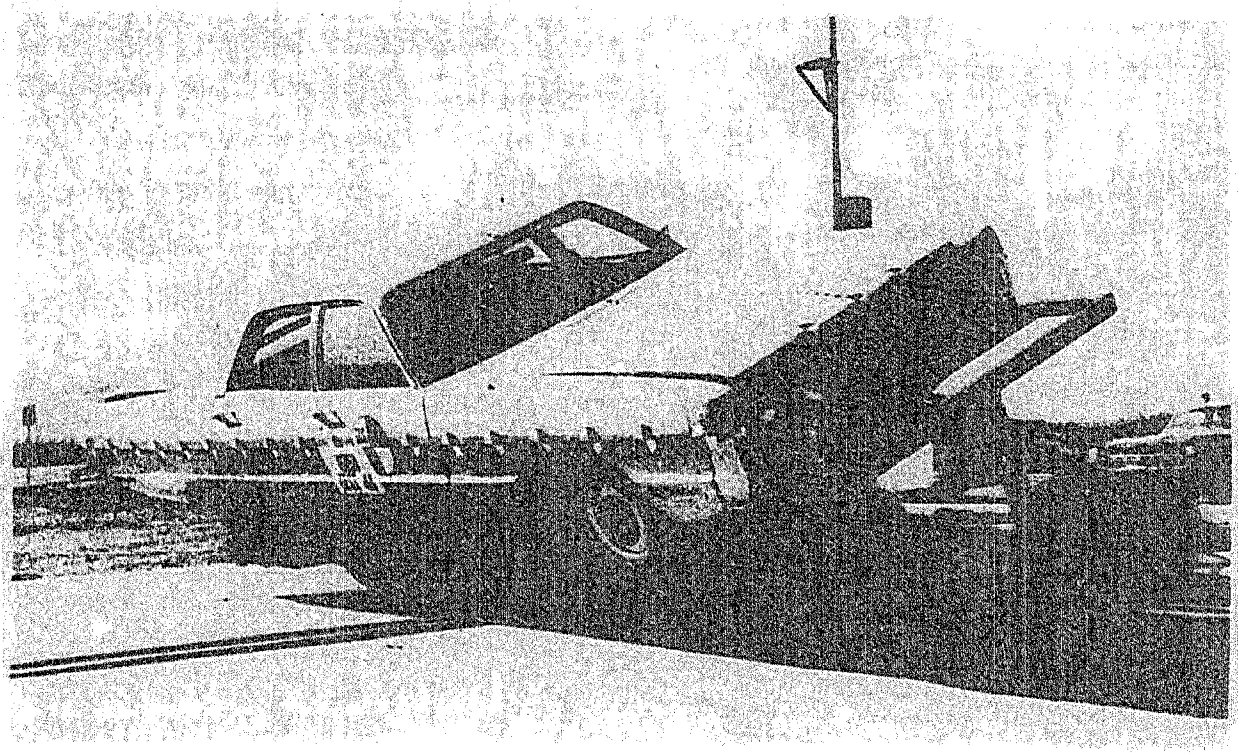

Figure 4-18. Rollover Test Vehicle Mounted on Dolly.

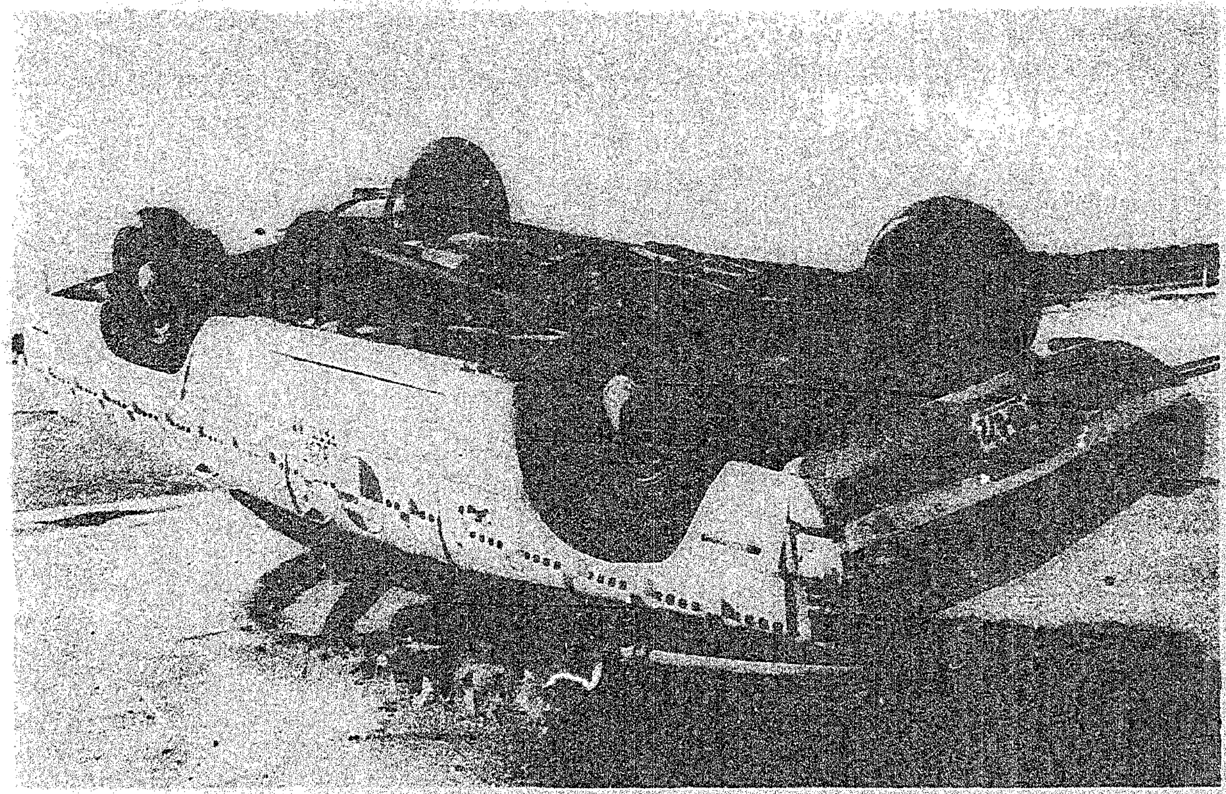

Figure 4-19. Post-test Position of Rollover Test Vehicle.

The vehicle structural damage is shown in Figure 4-20. There was no damage to the fuel system and no evidence of any spillage from the fuel tank or filler cap. There was no evident physical damage to the electrical system. However, the fire damage to the wiring in the engine compartment was extensive and made a complete evaluation difficult.

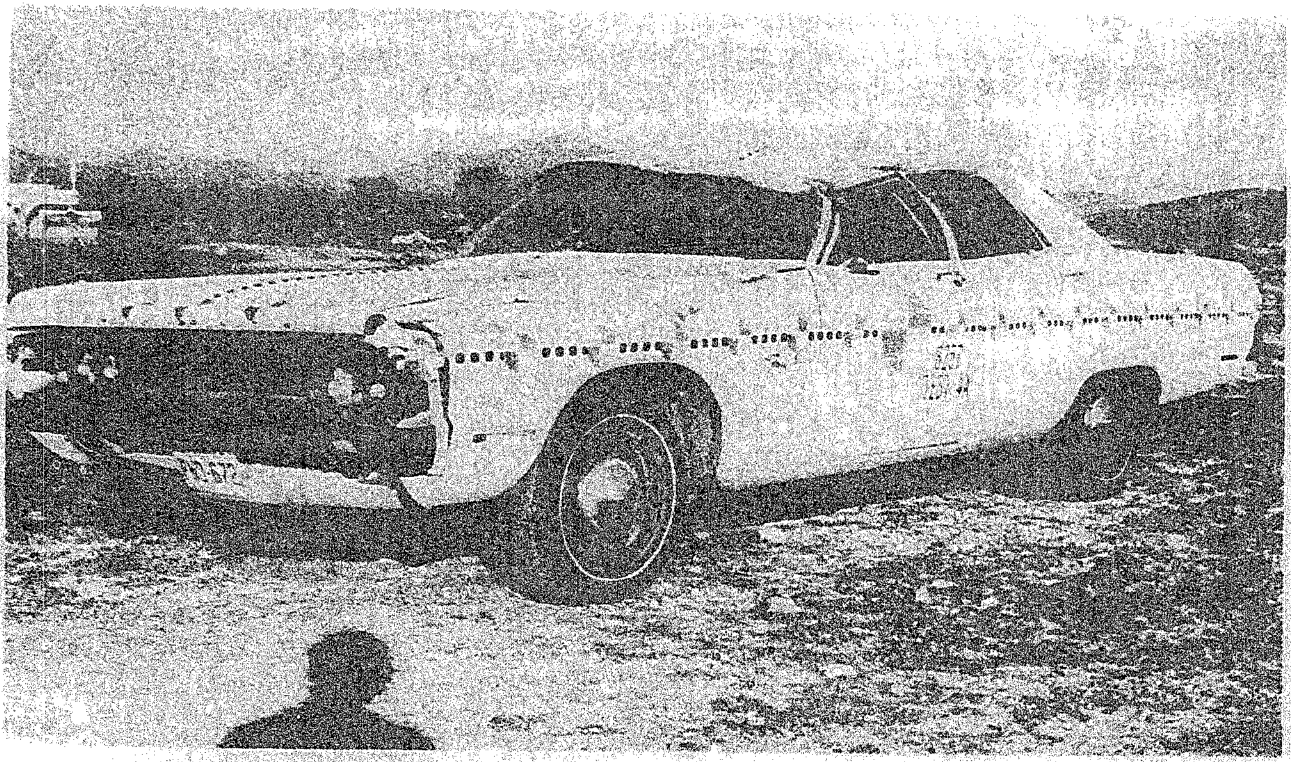

Figure 4-20. Structural Damage of Rollover Test Vehicle.

5.0 DEVELOPMENT OF COUNTERMEASURE SYSTEMS

5.1 GENERAL

The selection of specific countermeasures to prevent motor vehicle crash fires was based on the results of the literature survey, laboratory tests, and baseline crash tests. The countermeasures had to be practicable for use in standard automotive vehicles both from production feasibility and cost aspects. Since two controllable factors are required to initiate a fire, an ignition source and a flammable fuel, countermeasures were selected to control either ignition sources or fuel spillage. A cost/benefit analysis of the selected countermeasures was conducted to determine which of the countermeasures was most cost effective.

5.2 FUEL SYSTEM COUNTERMEASURES

Nearly all motor vehicle crash fires are gasoline-fed fires. If the gasoline is completely contained within the fuel system during and after a crash, the chances of the vehicle catching fire are minimal. This section discusses the fuel spillage countermeasures which were considered during the program.

5.2.1 Fuel Tanks

As noted in Section 2.4, which discussed available fuel system countermeasures, there are a number of safety fuel tanks commercially manufactured in the United States and overseas. A brief description of each tank follows:

AERO TEC LABORATORIES
Waldwick, New Jersey

- Tank wall material #421-D

  Rubber impregnated single-ply fabric. Used in the form of pillow-type bladder.

- Tank wall material #426-C

  Rubber impregnated two-ply fabric. Used in the form of bladder in metal canister. Can be filled with foam baffling.

- Tank wall material #PC-116

  Tank made of 3/16-inch high-impact thermoplastic material. Seamless construction with reinforced corners. Can be filled with foam baffling.

DONN ALLEN
Grants Pass, Oregon

- One-ply nylon fabric coated on both sides by polyurethane. Tank filled with reticulated polyurethane foam. Entire unit enclosed in 20-gauge steel canister.

FPT INDUSTRIES LTD.
Portsmouth, England

- Tank wall material #FPT/RS/669

  Lightweight, high-strength synthetic rubber reinforced with nylon fabric. Can be filled with reticulated polyurethane foam. Entire unit enclosed in steel canister.

FUEL SAFE CORPORATION
Huntington Beach, California

- Ballistic nylon fabric covered on one side by 3 layers of polyurethane. Tank wall is approximately 0.06 inch thick. Can be filled with foam baffling. The cells can be either contained in a canister or held in place by metal straps.

GOODYEAR TIRE AND RUBBER COMPANY
Akron, Ohio

- Goodyear Construction No. DX344, thin rubber sheet (no fabric) for standard automotive usage in metal shells.

- Goodyear Construction No. BTC-60-5. Made to NASCAR specifications. Rubber impregnated one-ply fabric. Unit to be installed in metal canister.

- Goodyear Construction No. BTC-60-9. Made to proposed USAC Specifications. Rubber impregnated heavy two-ply fabric. Unit to be installed in metal canister.

- Goodyear Construction No. BTC-60-10. Rubber impregnated heavy one-ply fabric. Unit to be installed in metal canister.

KLEBER COLOMBES
France

- Elastomer-base flexible material filled with reticulated polyurethane foam. Entire unit enclosed in steel canister.

MCCREARY TIRE AND RUBBER COMPANY
Indiana, Pennsylvania

- Seamless molded cell, made of DuPont "Hytrel". No fabric used. Has a base plate molded in and foam baffling installed. Filler assembly and metal canister not included.

SIMPSON SAFETY EQUIPMENT, INC.
Torrance, California

- Rubber-coated ballistic nylon. Used in the form of pillow-type bladder.

SUMITOMO ELECTRIC INDUSTRIES
Osaka, Japan and Los Angeles, California

- Tank Model #SCR

  Synthetic rubber-coated one-ply polyamide woven fabric. Can be filled with reticulated polyurethane foam or SAFOM; aluminum alloy fittings. Unit is contained in 20-gauge steel canister.

With one exception, all the tanks that were investigated were made of elastomer-coated fabric. This type of fuel tank provides greater safety from crash impacts than conventional metal tanks due to its superior properties in tear and puncture strength.

In order to select those safety tanks which were the most cost effective, a weighted rating scale was developed to evaluate the tanks in regard to cost, weight, production feasibility, necessary automotive design changes, interface requirements, complexity of manufacture, and effectiveness of tank construction in withstanding crash forces. The rating scale is shown in Table 5-1.

Each of the existing tanks was evaluated and a numerical rating assigned with a higher number indicating a more desirable

TABLE 5-1. RATING SCALE FOR SAFETY FUEL TANKS

Parameter	Scale				
Tensile Strength (lb):	10(≥1200)	9(≥1100)	8(≥1000)	7(≥900)	6(≥800)
	5(≥600)	4(≥500)	3(≥400)	2(≥300)	1(≥200)
Tear Strength (lb):	10(≥700)	9(≥500)	8(≥300)	7(≥200)	6(≥100)
	5(≥50)	4(≥40)	3(≥30)	2(≥20)	1(≥10)
Puncture Strength (lb):	10(≥350)	9(≥300)	8(≥250)	7(≥200)	6(≥180)
	5(≥170)	4(≥160)	3(≥150)	2(≥140)	1(≥130)
Availability of Tank Configuration:	10(any specified configuration)				
	7(some limitations)				
	4(much limitation)				
	1(total limitation)				
Fittings (rating based on durability, availability of specified design, whether flange is molded into tank body or merely bolted on, etc.):	10(excellent)				
	7(good)				
	5(fair)				
	3(poor)				
	1(undesirable)				
Need for Canister to Maintain Shape:	10(No)				
	5(Yes)				
Need for Separating Wall (20-gauge steel partition between tank and luggage compartment):	10(No)				
	5(Yes)				
Weight (includes weight of canister and/or separating wall) (lb):	10(≤15)	9(≤20)	8(≤25)	7(≤30)	6(≤35)
	5(≤40)	4(≤45)	3(≤50)	2(≤55)	1(≤60)
Cost per Unit (based on 100,000 units):	10(≤$20)	9($21-$30)	8($31-$40)	7($41-$50)	6($51-$60)
	5($61-$70)	4($71-$80)	3($81-$90)	2($91-$100)	1(≥$100)
Simplicity of Construction:	10(simple)				
	7(somewhat complex)				
	5(complex)				
	3(elaborate)				

evaluation. The tank ratings are shown in Table 5-2. Cost ratings were not included in the total tank rating since unit costs were not available from many of the manufacturers. Cost ratings are shown in parentheses where they were available.

5.2.2 Fuel Tank Relocation

The location of the fuel tank in most American cars is extremely hazardous from the standpoint of rupture during a rear impact; however, there are few alternative locations. A location above the rear axle is the only acceptable location which would provide an extra safety margin in a rear impact. The only other possible locations would be in the engine compartment or the passenger compartment. In the first case, the tank would be located where the majority of ignition sources exist. Even if a safety fuel cell were used, the possibility of fire in a severe crash would be higher than if the tank were located above the rear axle. A fuel cell located within the passenger compartment would provide a maximum safety factor against crush in either a front or rear impact; however, if a rupture did occur due to a side impact, fuel would be spilled into an area where certain death would occur if the fuel were ignited.

If a tank location above the rear axle is chosen, a firewall should be installed between the fuel tank and the passenger compartment. This firewall would be of greater importance if the existing galvanized tank were used instead of a safety fuel tank. In severe rear impacts, even though the tank might be above the rear axle, a considerable amount of damage could occur and a rupture would be likely in a metal tank. Without a firewall, gasoline would readily flow into the passenger compartment. Therefore, any relocation of the tank into the trunk area should be accompanied by the addition of a rear firewall.

5.2.3 Fuel Shutoff Valves

Fuel spillage must be prevented from every part of the fuel system if crash fires are to be eliminated. Therefore, a fuel

TABLE 5-2. SAFETY FUEL TANK RATING CHART

Manufacturer	Identification Number	Tensile Strength	Tear Strength	Puncture Strength	Availability of Tank Configuration	Fittings	Need for Canister	Need for Separating Wall	Weight	Cost	Simplicity of Construction	Total
Aero Tec Lab	421-D (15 gallon pillow - larger size won't fit)	6	7	6	3	2	10	5	8	-	9	56
	426-C	10	6	10	8	7	5	10	6	-	5	67
	PC-116	5	8	8	10	7	10	10	7	(4)	9	74
Donn Allen	-	7*	5*	5*	8	8	5	10	5	-	6	59
Firestone			DATA NOT MADE AVAILABLE BY MANUFACTURER									-
Fuel Safe	-	7	7*	7	9	9	10	10	7*	(7)	8	74
F P T	FPT/RS/669	10	6*	3	8	8	5	10	6*	-	5	61
Gene White				INSUFFICIENT INFORMATION								
Goodyear	DX 344	5	7	1	8	6	5	10	8*	-	6	56
	BTC-60-5	5	5	7	8	7	5	10	7*	(1)	6	60
	BTC-60-9	10	9	8	8	8	5	10	6*	-	6	70
	BTC-60-10	7*	6*	6*	8	7	5	10	7*	(1)	6	62
Kleber Colombes	-	4	6	7	8	7	5	10	6	-	6	59
McCreary	-	10	6	8	8	7	5	10	5*	-	6	65
Simpson	15 gallon pillow (larger size won't fit)	4	5	5	3	1	10	5	8*	-	9	50
Sumitomo	SCR	8	6	7	8	7	5	10	6	-	6	63
Uniroyal	D-755 or 751	7	7	8	8	8	5	10	7*	(6-7)	6	66

*Estimated from other data.

shutoff valve was considered to prevent spillage if the fuel line is broken. In the event the fuel line is broken between the fuel tank and fuel pump, the entire contents of the tank could be spilled if the vehicle comes to rest on its side or top.

Two inertia-actuated fuel shutoff valves were investigated. One, manufactured by Inertia Switch, Ltd. in England, was omnidirectional and required a preset 'G' level in any direction to operate. The second valve was manufactured for this program by Technar, Inc. This valve reacted to accelerations occurring during front or rear impacts but was insensitive to side impacts, although side impact sensitivity could be easily included in the design. The valve operated by gravity during rollovers.

Either of these switches could be located in the fuel line as it exits the fuel tank. In an impact all fuel would be shut off from the tank forward, and only the fuel remaining in the lines would be a potential problem.

In addition to the inertia-actuated fuel line shutoff valves, a valve was made available to this program by Aeroquip for use in preventing spillage from the carburetor during a rollover. (The carburetor float bowls in a rollover can spill their total contents in approximately 10 seconds, and although the fuel quantity is not large, it is adequate to start a fire.) Although the Aeroquip valve was not specifically designed for this application, it appeared to meet all the requirements. The unit was a ball-type valve which shut off when it was rotated 60 degrees from its vertical position. Modification of the end fitting and addition of another inlet allowed the valve to be used on a four-barrel carburetor. Its operation is illustrated in Figure 5-1.

Check valves located in the tank at the filler outlet were also considered. Although fuel systems containing evaporative emission controls (all 1971 and later models) utilize sealed filler caps, many of these caps will vent if the tank pressure exceeds 1 psi. Therefore, fuel can be forced out of the cap by hydraulic pressure in the tank during a rear-end impact or during

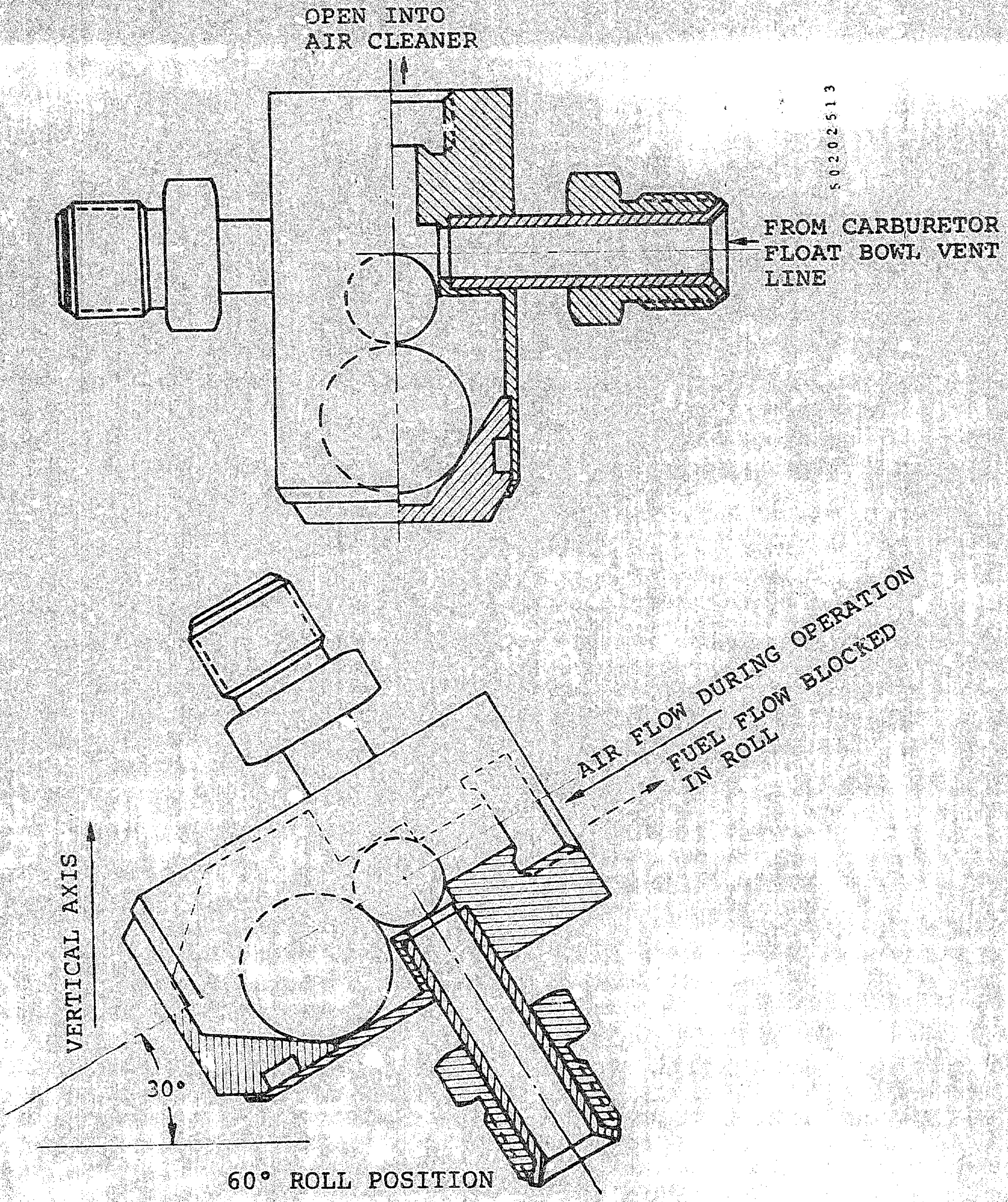

Figure 5-1. Carburetor Rollover Valve (Modified Aeroquip Valve) (2 Inlet Lines).

a rollover. A check valve in the filler outlet would prevent this leakage. Two of the safety tank manufacturers (Donn Allen and Aero Tec Labs) do provide flapper valves at the filler inlet if the customer so desires.

Another possible leakage point in the fuel system is the tank vent into the evaporative emission control system. Unless the liquid-vapor separator employs some type of liquid check valve, it is possible for fuel to flow from the tank into the vent line and storage container if the vehicle comes to rest on its top. If the storage container has been damaged or the vent line broken during the crash, fuel spillage will occur. Therefore, consideration was given to installing a simple ball check valve in the vent line such as is used in racing car fuel tank vent outlets.

Breakaway shutoff valves could be used in a fuel system to further increase its crashworthiness in those areas where fuel lines could be pulled and torn loose during a crash. Breakaway valves at these points would assure the line would separate at a predetermined location and the ends of the broken line would seal. These valves have been used in crashworthy aircraft systems but find limited use even in automotive racing because of their complexity and cost. They would, however, provide an additional safety margin for another failure mode.

5.2.4 Fuel Line Routing

To further reduce the possibility of fuel spillage, careful attention was given to line routing. Rerouting can be accomplished with a minimum of associated costs and greatly increase the fuel system crashworthiness. Areas of a vehicle where lines may be stretched in a crash should have adequate line slack to minimize the possibility of separation. Lines should also be routed to minimize damage by assuring that they follow areas of structural strength, such as the inside of the frame between the fuel tank and the engine. Fuel lines near the engine block can best be protected if the fuel lines are routed behind the front of the block to prevent them from being crushed against the block during a frontal crash. Adequate slack should also be provided the fuel line from the frame to the engine fuel pump so it cannot be pulled loose. Thus line routing is an easy method to accomplish a reduction in fuel spillage at a minimum cost.

5.2.5 Line Protection

In certain areas of the vehicle it is advantageous to use flexible or soft lines, particularly in the fuel line that runs from the frame area to the fuel pump. Soft lines in this area provide better fatigue characteristics against vibration than do hard lines. The standard rubber fuel line, however, is easily torn or cut in an accident. Steel braid covered rubber hose would provide a greater resistance to tears and cuts. Increased joint strength in these lines may be accomplished through the use of standard AN flare fittings with the armor-covered rubber hose.

Another design factor which could lead to line failure is line chafing due to a routing problem. Lines may be wrapped with a spiral spring to prevent wear in areas where rubbing could occur. Also, mounting the line with an adequate number of padded clamps will reduce line movement and chafing. Reducing weak points in the line will prevent line ruptures at those points during a crash.

5.3 ELECTRICAL SYSTEM IMPROVEMENTS

The second item which causes a fire is an ignition source in the presence of flammable gasoline vapors. The laboratory test results indicated that the primary ignition sources for automotive fires are electrical. This section discusses modifications in the electrical system which were considered to reduce the possibility of fire even if spilled gasoline is present.

5.3.1 Battery Protection

The position of the battery terminals and the current level available at these terminals present a very hazardous ignition source. Any contact of vehicle sheet metal with the exposed positive battery terminal in a negative ground system will allow in excess of 500 amperes to flow across the shorting gap until the metal is burned away by the action of the arc. Although some foreign manufacturers now protect the battery terminals from accidental shorting, most automobile manufacturers do not.

A simple plastic-over-lead cap could be designed and manufactured at a very low cost. This cap would only be required on the positive terminal since the rest of the vehicle is at the same ground potential as the negative terminal. This type of terminal protection would provide a higher degree of safety than do the thin rubber boots used on some cars. Also, a terminal modification would be less costly than redesigning the battery or installing the battery in a protective box. The shielded battery terminal would not only provide protection in case of a crash but would also prevent inadvertent shorting from metal tools contacting the battery terminal while working on the vehicle.

Figure 5-2 illustrates a shielded battery terminal which was designed by Ultrasystems during this program. The design assures that the positive battery terminal and cable attachment cannot be contacted by any metal. This particular device was designed for a test application and not for production. Under a production system, improved materials and methods of attachments could be used.

5.3.2 Battery Relocation

In most vehicles the battery is located near the front of the vehicle where it can be easily shorted due to structural deformation during a front impact. Therefore, relocating the battery was also considered to reduce direct battery shorts during a collision. A location under the rear passenger seat such as Volkswagen uses would be ideal from the standpoint of preventing shorts due to impact; however, servicing in this location is difficult. Relocation back toward the firewall, although not as good as under the back seat, would definitely be an improvement.

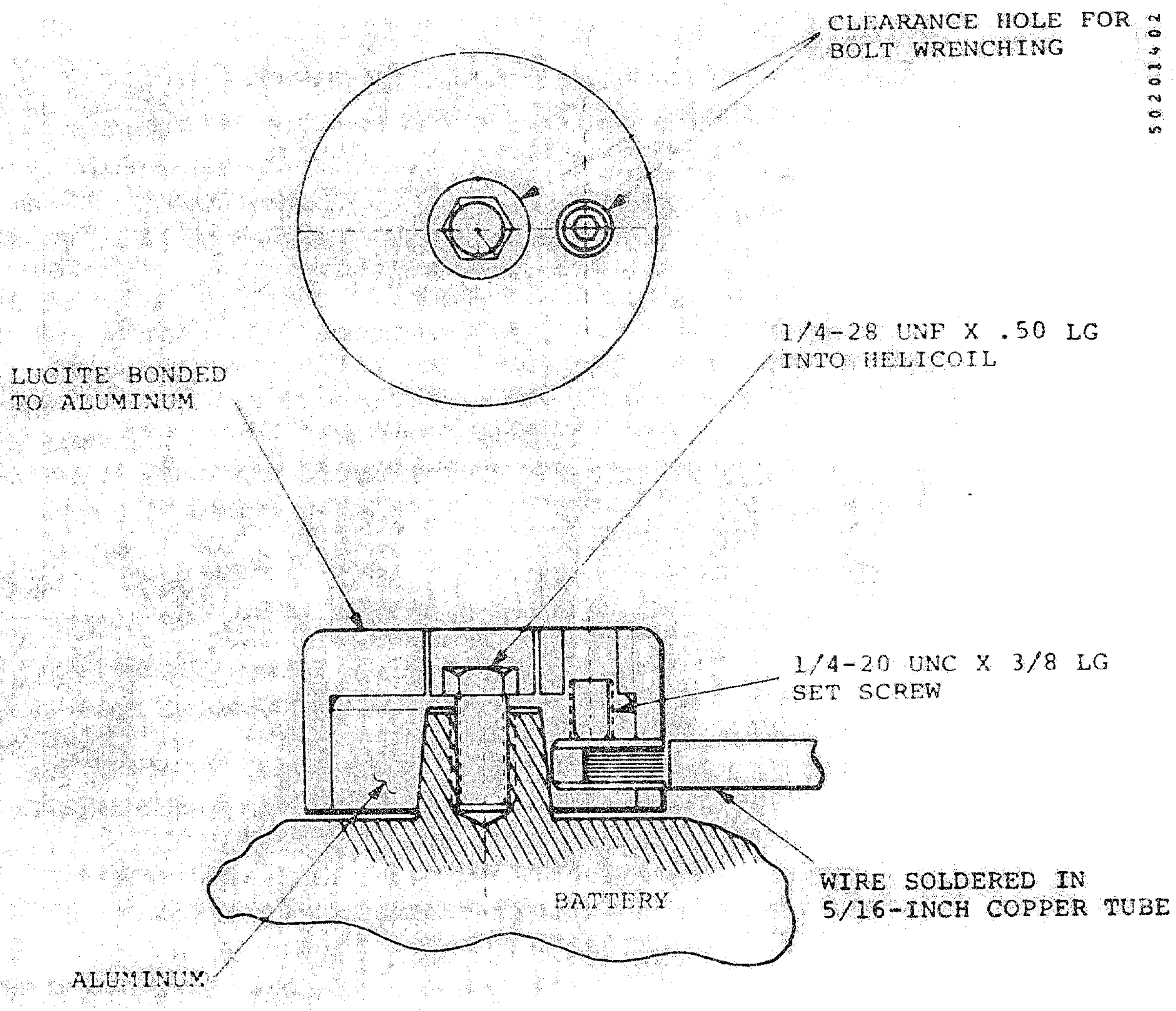

Figure 5-2. Shielded Battery Terminal.

The only difficulty with moving the battery to this location would be the cost to the automotive manufacturer since other engine compartment components might have to be relocated also to provide room for the battery. Battery terminal protection might provide a less costly answer to the same problem.

5.3.3 Wire Routing Modifications

The crashworthy design considerations which are true for fuel lines also hold true for electrical wiring. Providing adequate slack and preventing chafing are of prime importance. Wire routing changes in areas which are subject to damage are difficult. Headlights and their associated wiring must be located in the frontmost area of the vehicle to properly serve their function. The wiring itself may require improvements. Vehicles 10 years old or older start showing signs of cracked wiring insulation. This can present an increased risk in an accident where wiring, which would not normally short out when the car was newer, now shorts easily. This problem is less acute today than 10 to 15 years ago since some improvements have occurred in wiring insulation since then.

An additional vehicle wiring improvement which was considered was the addition of insulated sleeves over all exposed terminals. This would reduce shorting during an impact as well as inadvertent shorting while working on the vehicle.

5.3.4 Inertia Shutoff Switches

If a system is provided which shuts off the total vehicle electrical system at impact, many of the preceding improvements would not be required. Three manufacturers were contacted who made inertia switches of this nature for automotive applications. The general operating characteristics and mechanisms of each manufacturer's switch were discussed in Section 2.5. Table 5-3 lists the individual switches which were investigated during this program. Of the switches investigated, some provided a total system within a package, some used single functions, and others were inertia sensors only. Those three devices which are noted as sensors only provided a momentary contact switch and required a separate latching relay or solenoid to disconnect the vehicle power. All the manufacturers can provide switches which are sensitive to a wide range of 'G' loads.

These inertia switches were evaluated by means of a weighted rating scale similar to that used for evaluating the safety fuel tanks. This rating scale is presented in Table 5-4. The inertia sensors were rated with their separate related circuitry for comparison purposes.

TABLE 5-3. ELECTRICAL SYSTEM INERTIA SWITCHES

Device Test No.	Manufacturer's Number	Company	Function
S1	3562 (5.5G)	Inertia Switch Ltd, England	10A, 12V Electrical Circuit Shutoff Switch
S2	3566 (10G)	Inertia Switch Ltd, England	160A, 12V Battery Shutoff Switch
S3	3565 (5.5G)	Inertia Switch Ltd, England	10A, 12V Turn On Switch*
	356/12 (5.5G)	Inertia Switch Ltd, England	Combines 3562 and 3566 Function Into One Unit
	356/14 (5.5G)	Inertia Switch Ltd, England	Combines 3562, 3566, and 3565 Functions Into One Unit
S4	461 Sensor	Inertia Switch Ltd, England	Sensor with Gravity Roll Function; Requires Outboard Relay to Latch and Remove Battery Voltage
S5	Inertia Sensor	A.C.B. Corporation	Inertia Sensor; Requires Outboard Relay to Latch and Remove Battery Voltage
S6	Fire Chex	A.C.B. Corporation	Combines Main Battery Shutoff with Power Lead for Alternator; Performs Same Function as S7
S7	Air Bag Sensor	A.C.B. Corporation	Inertia Sensor; Requires Outboard Relay to Latch and Remove Battery Voltage if Used in this Mode
S8	Electrical Shutoff	Technar, Inc.	Provides 12V, 50A Shutoff; not for Main Battery Supply. Can be Produced for Main Supply.

*Typically used for functions such as initiation of fire extinguishing systems, flashing warning lights, etc. Was used during full-scale crash tests to turn on spark igniters.

TABLE 5-4. RATING SCALE FOR ELECTRICAL SYSTEM INERTIA SWITCHES

Parameter	Scale
Prior Use:	10(extensively used) 5(moderately used) 0(not used at all)
Operational Direction:	2 points each for switch operation on frontal impact, rear impact, left side impact, right side impact, rollover
Durability (rated on basis of construction, sturdiness, long-term stability, temperature range of operation, etc.):	10(very durable) 5(moderately durable) 0(weak)
Simplicity of Construction:	10(simple) 7(somewhat complex) 4(complex) 1(elaborate)
Dual Triggering Mechanism:	10(remote) 8(manual) 0(none)
Fail Safe Mechanism:	10(Yes) 7(No)
Volume cost/unit (100,000 units):	10(<\$1), 9(\$1-\$2), 8(\$2-\$3), 7(\$3-\$4), 6(\$4-\$5), 5(\$5-\$6), 4(\$6-\$7), 3(\$7-\$8), 2(\$8-\$9), 1(>\$9)
Functions Performed:	10(disconnects battery <u>and</u> isolates electrical system) 5(performs only one of these functions)

Table 5-5 lists the ratings of the various switches. A higher number indicates a more desirable evaluation. The two units manufactured by A.C.B. Corporation, FC 3121 and FC 212R, differ only in the remote reset feature.

TABLE 5-5. INERTIA SWITCH RATING CHART

Manufacturer	Prior Use	Operational Direction	Durability	Simplicity of Construction	Dual Triggering Mechanism	Fail-Safe Mechanism	Volume Cost/ Unit*	Functions Performed	Total Points (Out of Possible 80)
A.C.B. Corporation Lima, Ohio									
I.D. No. 3121	5	10	6	4	4	7	3	10	53
I.D. No. 212R	5	10	6	4	10	7	3	10	55
Inertia Sensor	0	10	6	4	10	7	6	10	53
Inertia Switch, Ltd. Hartley Wintney, England									
I.D. No. 3565	9	10	7	10	8	7	9	5	65
I.D. No. 3566	5	10	7	10	8	7	8	5	60
I.D. No. 3562	10	10	7	10	8	7	9	5	66
I.D. No. 356-12	0	10	7	10	8	7	8	10	60
I.D. No. 356-14	0	10	7	10	8	7	8	10	60
Technar, Inc. Arcadia, California									
Electrical Shutoff Switch	0	10	8	4	10	7	8	5	52

Note: Each factor is rated on a scale of 10.

*Estimated.

An inertia shutoff switch, in addition to removing all electrical ignition sources during a crash, also provides a means of disconnecting vehicle power when working on the car. Without the switch, disconnecting the electrical power generally requires removing corroded battery clamps which is so difficult that it is often not done. Disconnecting the battery will also generally stop a vehicle fire caused by an electrical short in the wiring, especially if the fire has just started. This again is a case where the battery cable must be removed to totally disconnect power unless an inertia switch is present.

The switch manufactured by Technar, Inc., requires 12 volts to function. When voltage is removed, the switch assumes an open state condition. Thus, when the power is removed from the switch, power is removed from the vehicle. This is easily accomplished from the driver's seat. One model of the Fire Chex switch from the A.C.B. Corporation can also be actuated from the driver's seat. The other has a button on the switch and must be operated from under the hood. Both A.C.B. devices require manual reset. The Technar device is electrically reset.

None of the devices manufactured by Inertia Switch, Ltd. are designed for remote electrical operation. The switches are totally mechanical and thus do not lend themselves to remote actuation as do the switches from the other two manufacturers. However, one car company is considering a mechanical switch which could be operated from the driver's seat. Thus all the switches investigated would be capable of also removing battery voltage in case of a non-collision electrical fire.

5.4 INERTIA-SENSITIVE COUNTERMEASURES SLED TESTS

A testing program was conducted to determine the impact characteristics of various inertia-sensitive devices when subjected to typical automobile crash decelerations. A deceleration sled and its associated instrumentation were used to determine the delay time after impact for switch actuation and the 'G' level at which actuation occurred. This test series helped to determine the strong and weak points of each switch design.

5.4.1 Test Facilities

The test facility consisted of a sled riding on two rails, a concrete deceleration pad, a tower fitted with a 5,600-pound accelerating weight, and a data acquisition trailer. The sled impact facility is shown in Figure 5-3.

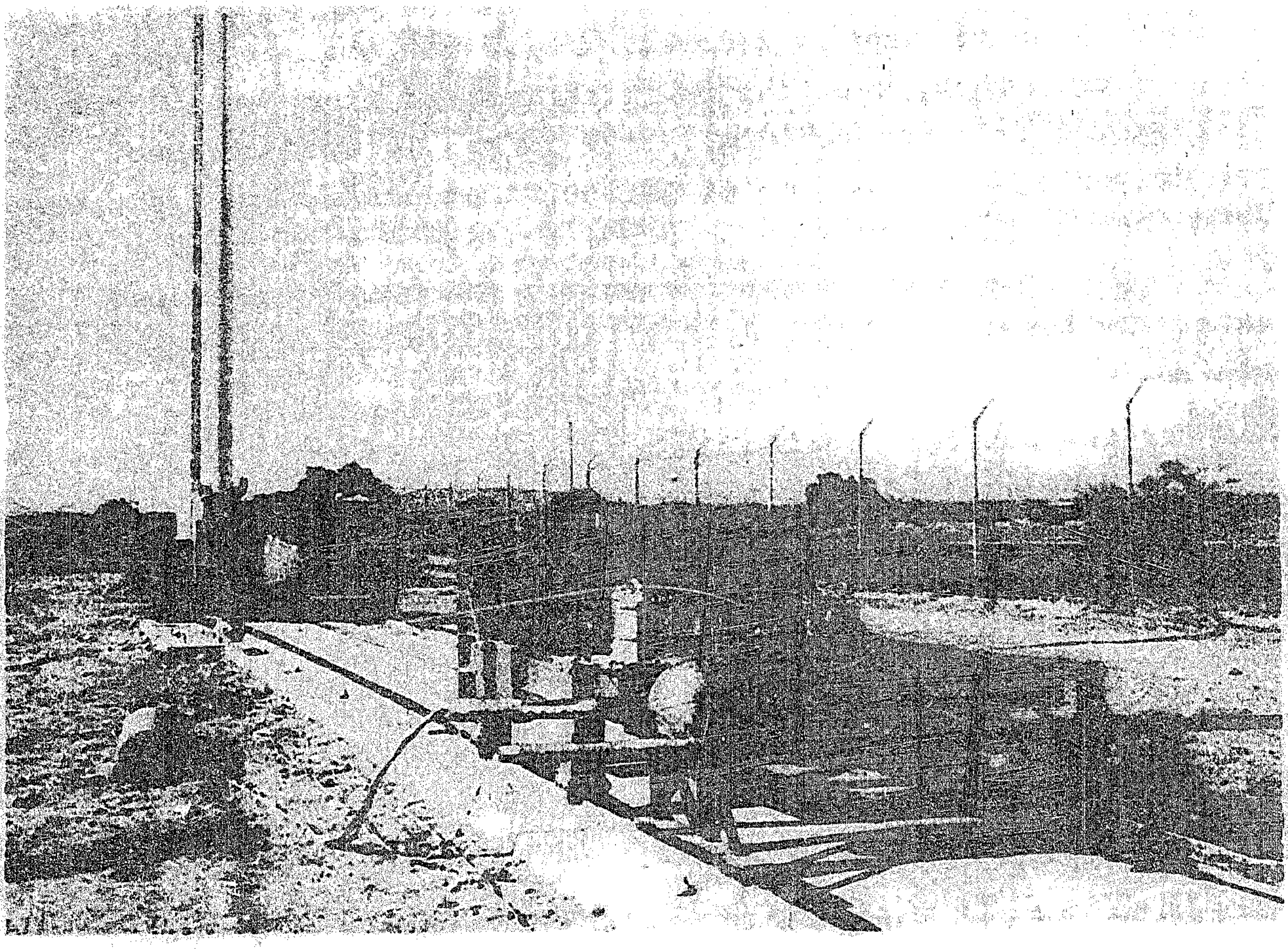

Figure 5-3. Sled Impact Facility.

The sled is composed of an I-beam construction. The rigidity of the structure adequately transfers the deceleration pulse to the items being tested on the sled. The sled rides the track on four wheels and is guided by steel plates on both sides of the wheels. A steel cable is attached to the front of the sled and goes through the concrete barrier to a set of pulleys which route it over the top of an 80-foot drop tower. The cable is attached to a 5,600-pound weight. When the sled is released from the winch mechanism, the falling weight pulls the sled into the barrier.

A pyramid of crushable paper honeycomb was mounted on the concrete barrier at the end of the track to provide the proper deceleration pulse. A standard computer program was used to determine the honeycomb stack size based on the sled weight and the velocity, rebound, and acceleration pulse desired.

The following instrumentation was used during each test:

Measurand	Transducer
Impact	Ribon Impact Switch
Sled Deceleration	200G Accelerometer
Sled Velocity	Break-wire Trap
Pressure Shutoff	100 psi Transducer
Inertia Switch Operation	Switch, on-off (voltage source)

Data received from this instrumentation was processed through on-board signal conditioning equipment driving an off-board recorder through a trailing umbilical. Sled velocity and impact were recorded directly without going through the signal conditioning. Data that was recorded was played back after the test on oscillograph traces for analysis.

5.4.2 Test Setup

The tests were run with the switches oriented in two different directions to simulate either a forward/rear impact or a side impact. Since most of the devices were omnidirectional, they were rotated 90 degrees from the longitudinal test position to the lateral test position. This indicated they would accept impacts 90 degrees from the previous location.

The last test of the series was designed to test the rollover capabilities of the switches. Those switches which operated inertially during a rollover were mounted so the top of the switch pointed 30 degrees forward of an inverted position during the simulated rollover test. This is the approximate vehicle angle at which the edge of the vehicle's roof contacts the ground in a rollover. Only the devices from Inertia Switch, Ltd. were of this nature. The remaining devices were gravity-sensing types of devices and could not be tested on the sled.

Figure 5-4 shows some of the devices tested during the sled tests. Eight electrical system shutoff switches from Inertia Switch, Ltd., A.C.B. Corporation, and Technar, Inc. were tested. Two fuel shutoff valves were also tested. (The fuel shutoff valves were obtained from Inertia Switch, Ltd. and Technar, Inc. and are described in Section 5.2.3.) The two fuel shutoff valves were connected to a pressurized air supply during the first six tests and to a pressurized water supply for the last four tests. Approximately 15-psi of pressure was fed to the valves through a 1/4-inch line. Pressure was sensed with a 100-psi transducer and bled off through a 1/16-inch orifice. This allowed the determination of shutoff time to within 5 msec or less. The shutoff of the electrical system switches was indicated by an on-off switch with a rise time of approximately 1 msec.

5.4.3 Test Results

The sled data from the tests are summarized in Table 5-6. A variety of impact velocities and decelerations were used during the test series to evaluate the operating ranges of the switches. Several tests were run at a very low deceleration to ascertain the minimum level necessary for switch actuation. All but two of the deceleration pulses were triangular in shape with a gradual rise to the peak deceleration followed by a rapid dropoff. High deceleration pulses lasting approximately 30 msec occurred near the end

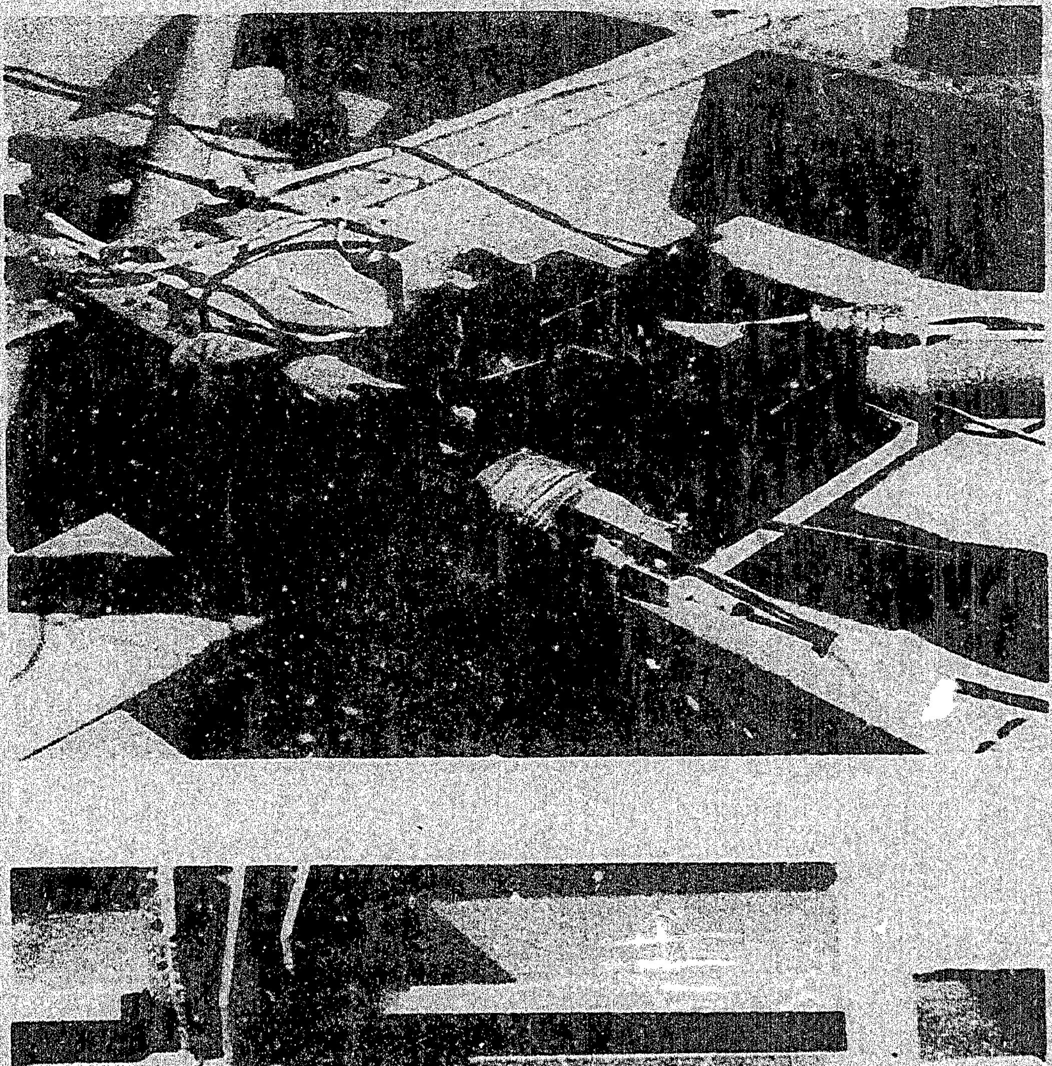

Figure 5-4. Inertia Shutoff Countermeasures Mounted on Test Sled.

TABLE 5-6. SLED TEST RESULTS - SLED DATA

Test No.	Device Orientation	Impact Velocity (ft/sec)	Peak G	Pulse Duration (msec)
1	Longitudinal	24.0	6	210
2	Longitudinal	36.0**	10	220
3	Longitudinal	36.3	12	178
4	Longitudinal	35.1	14	165
5	Lateral	35.7	10	215
6	Lateral	22.6	6	220
7	Longitudinal	47.0	27	105
8	Longitudinal	35.0	12	195
9	Longitudinal	24.0	29*	150
10	Longitudinal Inverted 30° (Rollover)	24.4	19*	170

*Honeycomb stack bottomed out resulting in a peak pulse higher than was anticipated.
**Data channel lost, estimate based on other tests.

of the pulses during Tests 9 and 10. These were caused by the honeycomb stacks bottoming out due to portions of the inner layers blowing out. The deceleration level just prior to the sharp deceleration change measured 6G during Test 9 and 8G during Test 10.

The recorded delay times from the start of the deceleration pulse to switch actuation for all the devices are presented in Table 5-7. (The switch numbers correspond to those listed in Table 5-3.) The initial closure time and length of closure are both listed for the sensor type switches since the closure pulse must be long enough to activate a latching relay or solenoid to effectively shut off the vehicle electrical system. Switches S4 and S7 were not tested during the first six tests because they were not received in time for these tests.

TABLE 5-7. SLED TEST RESULTS - INERTIA SWITCH ACTUATION TIMES

Test No.	I.S.L. 3562 S1	I.S.L. Ⓐ 3566 S2	I.S.L. 3565 S3	I.S.L. 461 Sensor S4	A.C.B. Inertia Sensor S5
1	N/O	N/O	90 ms	N/A	N/O
2	74 ms Ⓑ	N/O	48 ms	N/A	63 ms to 66 ms
3	72 ms Ⓑ	220 ms	24 ms	N/A	35 ms to 37 ms
4	35 ms Ⓑ	N/O	15 ms	N/A	22 ms to 24 ms
5	N/O	N/O	109 ms	N/A	157 ms to 159 ms
6	N/O	N/O	N/O	N/A	N/O
7	37 ms	57 ms	40 ms	58 ms to 368 ms Ⓓ	Ⓔ
8	116 ms	292 ms	128 ms	149 ms to 374 ms Ⓓ	294 ms to 295 ms
9	116 ms	90 ms	126 ms	150 ms to 195 ms Ⓓ	146 ms to 173 ms Ⓒ
10	68 ms	154 ms Ⓒ	78 ms	N/A	N/A

Test No.	Fire Chex S6	A.C.B. Air Bag Sensor S7	Technar S8	Technar Valve P1	I.S.L. Valve P2
1	N/O	N/A	N/O	Ⓗ	N/O
2	Ⓕ	N/A	N/O	Ⓗ	60 ms
3	158 ms Ⓕ	N/A	Ⓗ	Ⓗ	Ⓗ
4	126 ms Ⓕ	N/A	N/O	Ⓗ	Ⓗ
5	157 ms Ⓕ	N/A	N/O	N/O	Ⓗ
6	N/O	N/A	N/O	N/O	N/O
7	30 ms Ⓖ	24 ms to 85 ms	Ⓗ	Ⓔ	Ⓗ
8	148 ms Ⓖ	309 ms to 314 ms	Ⓙ	Ⓔ	Ⓗ
9	148 ms Ⓒ	140 ms to 167 ms Ⓒ	N/O	96 ms	Ⓗ
10	N/A	N/A	N/A	N/A	Ⓗ

N/A - Indicates device was not used during this test.
N/O - Indicates no operation, conditions were out of switch range.
Ⓐ - Set for 10G for Tests 1-6, and 5.5G on Tests 7-10.
Ⓑ - Data indicates switch remade circuit after short time delay. However, observation at the end of each test would not substantiate this; possible instrumentation difficulty.
Ⓒ - Occurred as a result of high "G" peak where honeycomb was bottomed out.
Ⓓ - Continuity was made and broken during sled run prior to impact.
Ⓔ - Data channel lost.
Ⓕ - Main system inoperative; data taken from accessary output.
Ⓖ - Main system would not maintain open circuit; time indicates initial circuit opening.
Ⓗ - Off prior to impact due to low level primary sled acceleration-3"G" level.
Ⓙ - Unable to reset; incorrect battery polarity.

Examination of the data in Table 5-7 shows that none of the switches actuated during Test 6 which used the lowest deceleration (6G) and slowest impact velocity (22.6 ft/sec). Only one switch (S3) actuated during Test 1 which exhibited the same peak deceleration but slightly higher velocity than Test 6. Although the manufacturers could design the switches to actuate at these low levels, it would be unwise to do so since they could actuate during normal, if somewhat severe, operating conditions. This is evident by the reactions of both fuel system shutoff valves which closed during the initial acceleration of the sled before it reached its final velocity. This problem was corrected with the Technar valve when water was used in the valve for Tests 7 to 10 instead of air. Technar had indicated after the first tests that fluid was necessary to provide the damping action which their valve required.

All but two of the switches actuated under a peak 10G deceleration and 36 ft/sec impact velocity. All but one switch actuated during all of the remaining higher deceleration tests. The Technar switch (S8) did not operate during any of the tests, and consultations with the manufacturer failed to disclose the reason. However, it should be noted that this was a prototype switch built on very short notice specifically for this program. Since the basic design of the switch has been used successfully for several years in other applications, it would be safe to assume that a small amount of effort would produce a switch that would operate under the conditions of these tests.

The closure times recorded for the A.C.B. inertia sensor (S5) were very short (2-4 msec) during the lower deceleration tests. Since a separate latching relay or solenoid must be used with the sensor in order to shut off the vehicle electrical system, this short closure time creates a problem in the selection of the secondary switch. There are some commercially available latching relays which will function with such a short electrical pulse, but they are designed for highly specialized applications and are thus rather costly.

The instrumentation circuit which sensed the actuation time of the Fire Chex switch was initially coupled to the main grounding system which breaks the battery circuit. Although the solenoid did operate during Test 2, the switch did not break the circuit and the actuation time was not recorded. Subsequent tests were conducted by sensing the actuation time off of the wire which runs to the distributor side of a vehicle's ignition coil (see Figure 2-10). The manufacturer of the Fire Chex switch indicated that the problem in the closure mechanism has been corrected in a later design.

During Test 8, three of the switches (S2, S5, and S7) failed to actuate during the initial deceleration pulse but did actuate as the sled stopped its rebound motion. Although the sled did stop rather abruptly, the deceleration levels were not much higher than those experienced during the initial pulse and were of an extremely short, vibratory nature with a very small overall change in velocity. No explanation could be found for the switches actuating at this time and not during the initial deceleration pulse.

5.5 SELECTION OF COUNTERMEASURES TO BE DEMONSTRATED

The full-scale demonstration crash tests which were to culminate the program were designed to evaluate and demonstrate the effectiveness of selected countermeasures for both ignition sources and spilled fuel. The goal of the countermeasures selection was to provide adequate protection from post-crash fires in the most practical manner, both from production feasibility and cost aspects. To incorporate all the countermeasures previously discussed would be very costly as well as being redundant in many areas. Therefore, only optimum countermeasures were selected, based on the results of the literature survey, laboratory testing, baseline crash testing, and countermeasures evaluation.

5.5.1 Selection of Fuel System Countermeasures

Prevention of fuel spillage in moderate to severe rear-end accidents can best be achieved by relocating the fuel tank from its present location under the trunk floor or in the rear quarter panel to a position above the rear axle. This would allow several feet of vehicle crush to occur before intrusion into the fuel tank area. The installation of a standard metal tank in this area would probably provide protection in moderate (up to 25-30 mph) rear-end collisions. However, for more severe accidents (in which the majority of fires occur), a safety fuel tank would be necessary.

The selection of a fuel tank for the 60-mph front-to-rear demonstration crash test was based on the results of the safety fuel tank evaluations. The Fuel Tank Rating Chart (Table 5-2) shows that the Aero Tec Laboratories (ATL) PC tank and the Fuel Safe tank both received identical highest ratings. Therefore, one of these tanks would be procured for the front-to-rear test.

It was also decided that the same type of fuel tank installation should be used in the demonstration rollover test. This decision was based on the necessity of demonstrating that the installation of a tank for rear-end crash protection was also safe during a rollover. Since the rear impact was a decidedly severe test, the possibility existed that even the safety fuel tank might be damaged during the test, thus leaving no fuel tank available for the rollover test. Therefore, it was felt necessary to procure two safety fuel tanks. Since the ATL and Fuel Safe tanks were ranked equally high, one tank was procured from each manufacturer for the demonstration tests. This allowed both tanks to be personally examined by the investigators to determine which tank, if either, might be more satisfactory.

In order to prevent fuel spillage from the filler during the rollover test or due to hydraulic ram pressure from the tank being crushed during the rear impact, it would be necessary to provide some type of check valve in the filler outlet. The simplest type of valve for this purpose is a flapper valve. The tank filler plate manufactured by ATL contains such a valve and, therefore, an ATL filler plate was procured for use in each of the fuel tanks. The plate contained a 2-1/4-inch filler pipe with the flapper valve, two fuel return line fittings, one fuel outlet line fitting, and one vent line fitting (see Figure 2-5(b)).

Examination of the flexible flapper valve, which was supported in the closed position by two metal strips at right angles to each other, disclosed that some leakage could occur near the unsupported areas of the valve. Therefore, two additional supporting strips were added before the plate was installed for the demonstration tests.

Breakaway valves and inertia fuel shutoff valves were also considered as candidate countermeasures. However, it was felt that careful routing of the fuel lines and proper line and fitting selection would be sufficient to prevent line failure. This solution is far preferable to installing breakaway valves since these valves are quite expensive and are not designed or produced for automotive applications at the present time.

Although an inertia fuel shutoff valve in the engine compartment could be used to prevent fuel spillage from a severed fuel line, it was felt that proper line routing and selection would again be preferable and accomplish the objective of preventing fuel spillage.

A liquid check valve in the vent line was deemed necessary to prevent fuel spillage during both the rear impact and rollover should the vent line be damaged. Even if there is no danger of vent line damage, this countermeasure should be included in those vehicles which contain carbon canisters for vapor storage since fuel can run through an undamaged vent line and spill from the canister if the vehicle comes to rest in a nose-down attitude. The check valve selected for demonstration was a liquid-vapor check valve manufactured by American Motors for their cars. Selection was based primarily on a judgment that the design was adequate and the valve was readily available for automotive applications.

In order to prevent fuel spillage from the carburetor, the modified Aeroquip rollover valve (Figure 5-1) was selected for use during the rollover test. This valve was selected because it offered a simple yet effective way of eliminating carburetor fuel spillage.

5.5.2 Selection of Ignition Source Countermeasures

The laboratory testing conducted earlier in the program had shown that sparks from the vehicle's electrical system and exposed, lighted headlamp filaments were by far the most prevalent crash fire ignition sources. The use of an inertia electrical system shutoff switch would eliminate all such ignition sources with the exception of sparks generated by metal coming in contact with the positive battery terminal. This switch should shut off all vehicle electrical power as soon as possible after the initial impact, including current from the alternator which would be present if the engine continued to run.

The selection of the inertia switch(es) to be used during the demonstration tests was based on the inertia switch rating evaluation and the results of the sled tests. The Rating Chart (Table 5-5) shows that the Inertia Switch, Ltd. switches all received a higher rating than the other switches. This was due in large part to their simpler construction which was given a higher rating than the more complicated designs. The reliability of this simpler design was apparent from the results of the sled tests. Although some of the sensor type devices also worked well, the additional cost of procuring and installing the separate latching relay or solenoid required could not be justified when there were satisfactory switches available which did not require these extra components.

A 356/12 switch, which shuts off the alternator electrical circuit and the main battery power, was ordered from Inertia Switch, Ltd (see Table 5-3). However, it was not received in time for the demonstration tests. Therefore, two switches from Inertia Switch, Ltd. which had been used during the sled tests were selected for the demonstration tests. The 3566 switch (set for 5.5G) would be used to remove the main battery power and the 3562 switch would be used to shut off any current from the alternator.

It was also considered necessary to prevent possible sparking generated by metal coming in contact with the positive battery terminal. The plastic terminal protector designed by Ultrasystems (see Figure 5-2) was selected over other concepts because of its simplicity and ease of fabrication.

With the battery terminal protected, it was not considered necessary to relocate the battery to prevent it from being damaged since internal sparking would be very unlikely to occur. Also, the rerouting and/or protecting of electrical wiring was not considered necessary because of the use of the electrical system shutoff switches.

Although friction sparks can function as ignition sources, they do not pose nearly as much of a hazard as do electrical sparks. In addition, there is no practical way of eliminating friction sparks as long as automotive structures are made of steel. Therefore, no countermeasures were selected to prevent the occurrence of friction sparks. Instead, it would be much more practical to eliminate all fuel spillage to prevent fires caused by this ignition source.

5.6 COST/BENEFIT ANALYSIS

A cost/benefit analysis study was conducted to determine which countermeasure systems would be most beneficial to the public on a cost basis. Two different systems were analyzed. They were:

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1. A system which combines selected fuel spillage and ignition source countermeasures to eliminate post-crash fires.
2. An electrical countermeasures system which removes the majority of ignition sources leading to post-crash fires.

The basic methodology for conducting the cost/benefit analysis on each system was identical. The methodology and analysis results are presented in the following sections.

5.6.1 Methodology

Initial plans were to base the cost/benefit analyses on the following factors:

1. Total (nationwide) fatalities, injuries, and accidents projected from 1975 to 1995.
2. Frequency distribution of compact, standard, and other vehicles in each given year of analysis.
3. The probability of vehicle fire given a crash has occurred for each type of accident and vehicle.
4. The effectiveness of the countermeasure system within the given class of accident occurrence.
5. The probability of the vehicle containing the system (as compared to all vehicles on the road in each year under investigation).

However, it was necessary to deviate from the proposed analysis due to the limited data available for two of the above categories.

It was not possible to assign a fire risk factor on the basis of vehicle type because of the extremely limited fire accident data in this area. Those few reports that contained such data utilized such small sample sizes that any extrapolation to the nationwide vehicle population would have been very unreliable.

Defining the fire risk in relation to the type of accident with any confidence was also impossible. This was due to the different methods of classifying accidents in the various fire accident reports. Rollovers were the major problem. In some cases all rollovers were categorized under one heading. In other cases the rollover was included with a front, rear, or side impact depending on the initial impact area of the vehicle involved. Some reports classified primary rollovers under one heading while the remainder of the rollovers were grouped together in another category. This inconsistency in data reporting prevented the use of impact vectors in the analysis.

Therefore, the cost/benefit analysis was based on:

1. nationwide motor vehicle fatalities and accidents
2. projected fire fatalities, injuries, and accidents
3. effectiveness of the countermeasure system in preventing fires
4. number of vehicles containing the system.

Total vehicle fire costs, if no countermeasures were utilized, were calculated using the following equation:

$$C_i = F_i \cdot P(F) \cdot C(F) + F_i \cdot P(F) \cdot P(I) \cdot C(I) + F_i \cdot P(F) \cdot P(D) \cdot C(D) \qquad (5\text{-}1)$$

where C_i = total vehicle fire cost for year i

F_i = total nationwide fatalities for year i

$P(F)$ = probability of fatality resulting from burns

$C(F)$ = societal cost of fatality

$P(I)$ = probability of burn injury in relation to fire fatalities

$C(I)$ = societal cost of burn injury

$P(D)$ = probability of vehicle being involved in fire in relation to fire fatalities

$C(D)$ = property damage cost of vehicle involved in fire accident

The above factors were derived as follows:

1. The probability of a fatality occurring as a direct result of burns was based on 1.4 percent of all motor vehicle fatalities (excluding pedestrians and bicyclists) being caused by burns. This number was derived from the literature survey as discussed in Section 2.1.1.

2. Burn injuries were estimated as being equal to burn fatalities. As noted in Section 2.1.1, data on burn injuries is practically non-existent. However, the estimate of one burn injury for every burn fatality does agree closely with the very limited amount of data available in the New York report (Reference 4).

3. The probability of a vehicle being involved in a fire was based on the projected minimum number of 5000 fire accidents per 625 fire deaths derived in Section 2.2.1. This factor was multiplied by 1.4 to arrive at the total number of vehicles involved in fire accidents. The multiplier of 1.4 is the minimum ratio of number of vehicles per accident contained in Reference 2.

4. Fire fatality costs of $212,800 per fatality were obtained from Societal Costs of Motor Vehicle Accidents (Reference 19) with a 6 percent inflation factor added to reach 1973 levels.

5. Fire injury costs of $92,220 per injury were obtained by adding $21,094 to the injury costs given in Reference 19. The additional cost due to burns was obtained from Reference 20.

6. Property damage costs of $700 per vehicle were taken from data in Docket 70-20 pertaining to FMVSS 301, Fuel System Integrity (Reference 21).

7. Total nationwide vehicle fatalities were projected to 1995 based on projections of vehicle miles traveled and death rates per 100,000 miles. Figure 5-5 shows the projection of vehicle miles traveled through 1995. This projection was based on data contained in Reference 2 which shows that the vehicle miles traveled doubled every 16 years from 1935 through 1973. Even though the rate dropped during the years of World War II, it recovered and continued almost as if the war years were not there. The extrapolation to 1995 does not speculate in regard to what effect an energy crisis

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19. Societal Costs of Motor Vehicle Accidents, NHTSA, Department of Transportation, Washington, D.C., Preliminary Report, April 1972.
20. King, Barry G., Jr., et al., Motor Vehicle Accidents and Burns: An Epidemiologic Study of Motor Vehicle Fires and Their Victims, Proceedings of 16th Conference on the American Association for Automotive Medicine, October 1972.
21. Grush, E. S., and Saunby, C. S., Fatalities Associated With Crash Induced Fuel Leakage and Fires, Ford Motor Co. Interoffice Report to NHTSA Docket Section, Docket 70-20, Washington, D.C., September 19, 1973.

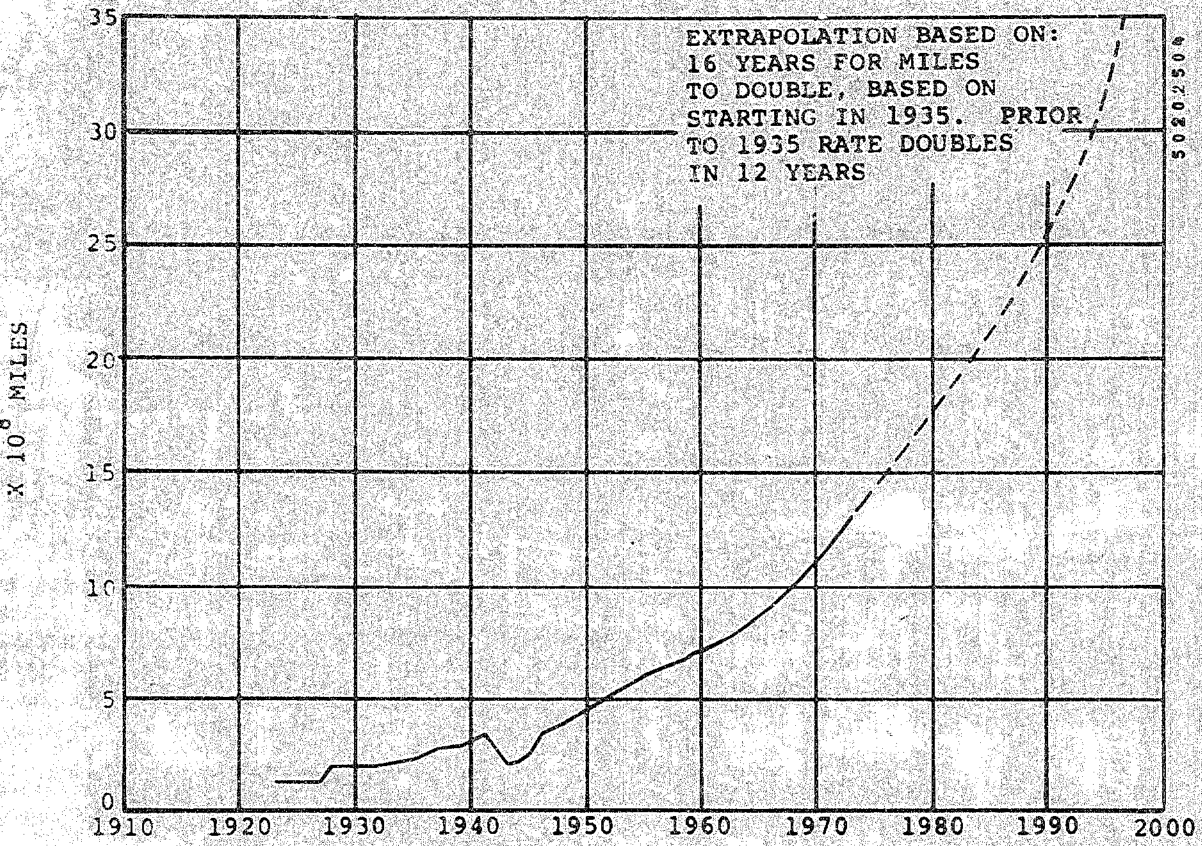

Figure 5-5. Vehicle Miles Traveled.

may have. However, the period following World War II shows that, when the crisis was over, mileage resumed its upward travel with no loss in rate.

Figure 5-6 indicates the death rate per 100,000 vehicle miles traveled. The data from prior years (Reference 2) shows that it took 24 years to decrease the death rate by 50 percent. This data was also extrapolated to 1995.

The results of these two graphs were used to project vehicle fatalities to 1995. This method of determination provided a clearer trend line than could be obtained from past fatality data alone. Figure 5-7 shows these projections for total fatalities and for fatalities where only motor vehicles are involved. Trace 1 in Figure 5-7 indicates total fatalities which include

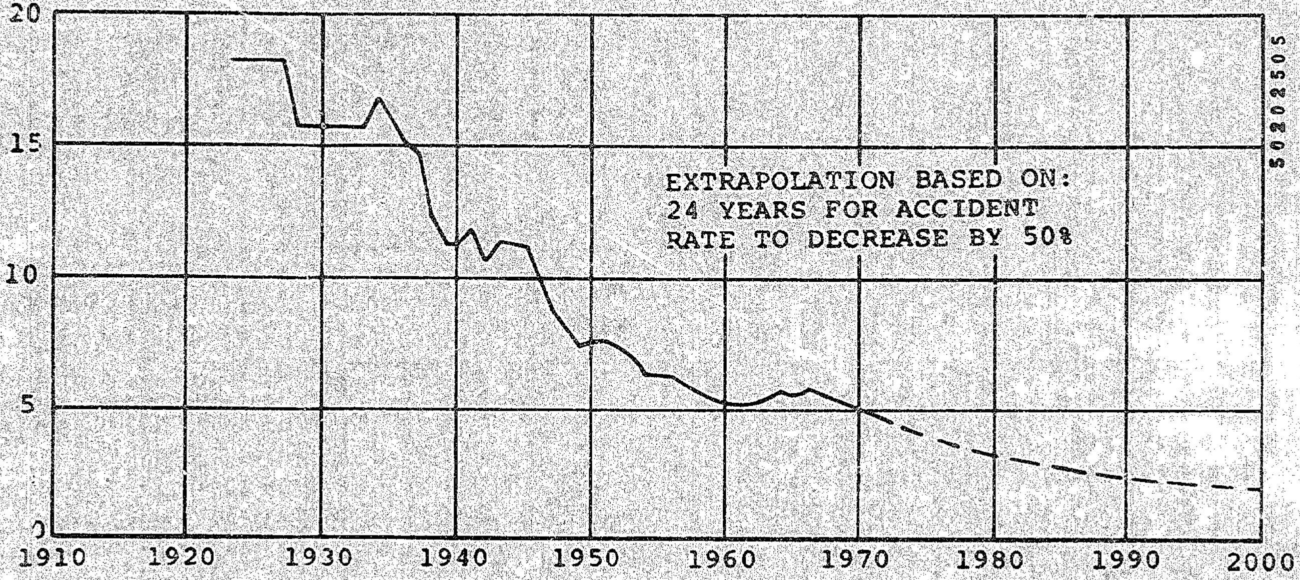

Figure 5-6. Death Rate Per 100,000 Vehicle Miles.

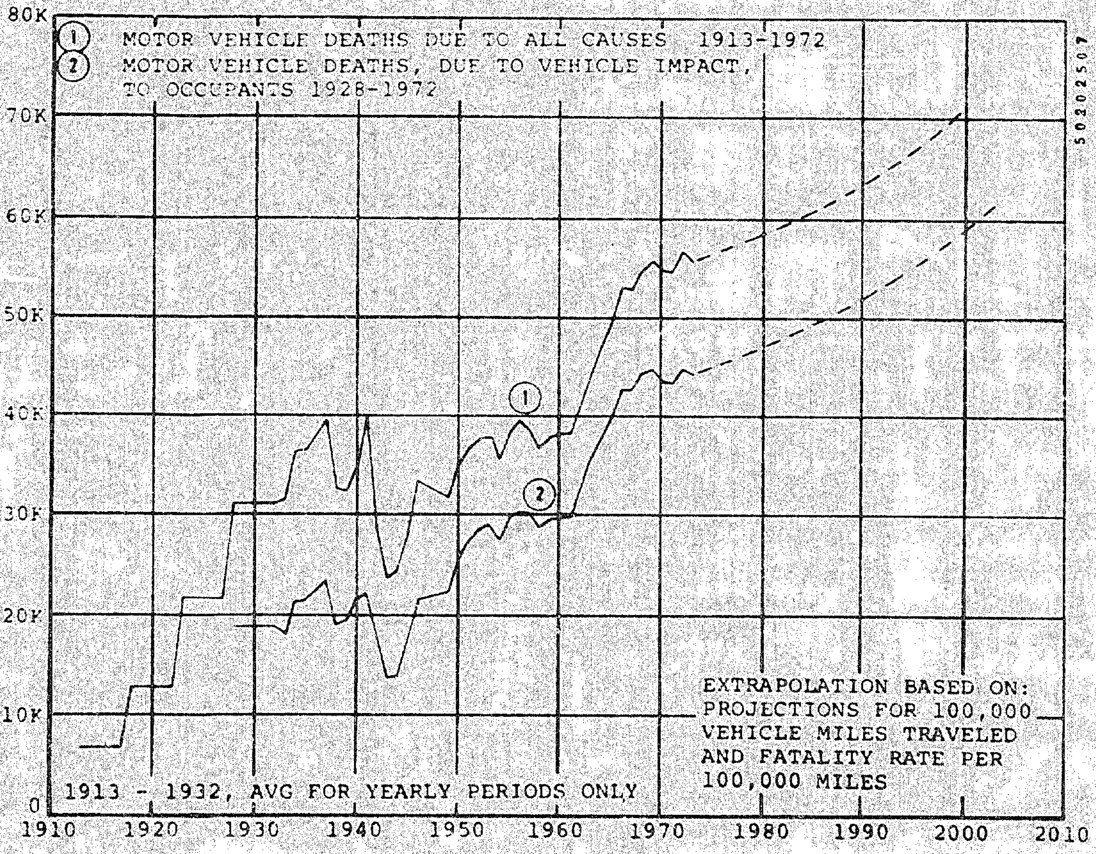

Figure 5-7. Motor Vehicle Fatalities.

pedestrians and bicycles. Trace 2 shows only fatalities which were a direct result of driving or being a passenger in a motor vehicle. These fatalities include people who died in vehicle fires.

1973 was chosen as the base year since a major portion of the data available was for this year. Also, it was the latest year for which data were available on national fatalities and accidents. All dollar figures are in 1973 base year dollars with no attempt being made to add inflationary trends. The base year cost data is shown below:

Fatality Cost	617 @ $212,800 =	131,297,600
Injury Cost	617 @ $ 92,220 =	56,899,740
Property Damage	6910 @ $ 700 =	4,837,000
		$193,034,340

The economic savings due to the installation of the countermeasure systems were calculated using the following equation:

$$S_i = C_i \cdot U_i \cdot E - V_i \cdot C(C/M) \qquad (5\text{-}2)$$

where S_i = economic savings in year i

C_i = total vehicle fire cost for year i

U_i = probability of involved vehicle using countermeasure system

E = effectiveness of countermeasure system

V_i = number of vehicles with countermeasure system

$C(C/M)$ = cost of countermeasure system

The above factors were derived as follows:

1. Total vehicle fire cost was calculated from equation (5-1).

2. The probability of a vehicle using the countermeasure system was based on projected new vehicle registrations combined with the percentage of older vehicles still in use. New vehicle registrations were based on 1962 through 1971 vehicle registrations as obtained from Reference 22. This data included all passenger cars and light trucks less than 10,000 pounds GVW. The data were extrapolated based on a trend line of 7-1/3 years for new vehicle registration to increase by 1 million vehicles. The percentage of vehicles with countermeasures was extrapolated from percentages of older vehicles remaining in service from 1955 through 1971 as obtained from Reference 22.

3. The effectiveness of the countermeasure system was based on the results obtained during earlier phases of the program. This factor will be discussed later during the analysis of each system.

4. The cost of each countermeasure system was based on manufacturers' and Ultrasystems' estimates. Costs will be discussed during the analysis of each system.

5.6.2 Combined Ignition Source and Fuel Spillage Countermeasures

This system would utilize a safety fuel tank, including a filler check valve, located above the rear axle to control the majority of fuel spillage from vehicle accidents. It would also include a firewall between the fuel tank and passenger compartment. Electrical ignition sources would be eliminated by the use of an electrical system inerting switch and a shielded battery terminal. This combined system would be superior to a strictly crashworthy fuel system which controlled fuel spillage in the engine compartment for two reasons. The cost of a carburetor rollover valve, inertia fuel shutoff valve, and associated fuel line modifications would be more expensive than the electrical system countermeasures. In addition, the vehicle could still function as an ignition source for fuel spilled from an unmodified vehicle until such time as all vehicles contained the crashworthy fuel system.

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22. Automotive News Almanac, Crain Communications, Inc., Detroit, Michigan, 1972.

The cost of the combined electrical and fuel system countermeasures was estimated at $35.00. This cost is accounted for as follows:

	Item	Cost
1.	Shielded Battery Terminal	$ 0.50
2.	Safety Fuel Tank	30.00
3.	Filler Check Valve	0.50
4.	Electrical Inertia Switch	2.50
5.	Separating Fire Wall	1.50
		$35.00

The cost of the safety fuel tank is the additional cost above that estimated for the present fuel tank. This cost could actually be somewhat higher since it was not possible to obtain the exact cost of the present tanks. Tank relocation cost was omitted due to a lack of retooling cost information from the manufacturers and also because the cost would be an initial cost only and not a yearly recurring cost. Thus the $35.00 is an absolute minimum estimated manufacturing cost and does not include any profit or other burden that might be passed on to the consumer.

Since the vehicles incorporating this combined countermeasure system would not contribute as an ignition source or a source of spilled fuel during an accident, the system was considered approaching 100 percent effectiveness. Thus an effectiveness factor equal to the percent of vehicles with the system was assigned for the cost/benefit analysis.

The results of the analysis are shown in Table 5-8. The figures indicate that the savings with the countermeasures system would approach 50 percent of the total costs of the system per year and would remain near that level even after all of the vehicles contained the system. It should be remembered, however, that the analysis was based on the minimum projected number of

TABLE 5-8. COST/BENEFIT ANALYSIS OF FUEL AND ELECTRICAL COUNTERMEASURES SYSTEM*

Year	Fire Cost Without System ($ Million)	Percent Vehicles With System	System Effectiveness Factor	Fire Savings With System ($ Million)	New Vehicles Registered (Million)	System Cost Per Vehicle ($)	Total Vehicle Costs ($ Million)	Savings/Cost Ratio (Per Year)
1976	198.98	0	0	0	11.45	0	0	0
1977	200.77	10.0	.100	20.08	11.59	35.00	405.65	0.05
1978	202.42	20.0	.200	40.48	11.72	35.00	410.20	0.10
1979	204.61	30.1	.301	61.59	11.86	35.00	415.10	0.15
1980	206.49	40.0	.400	82.60	11.99	35.00	419.65	0.20
1981	208.36	49.8	.498	103.76	12.13	35.00	424.55	0.24
1982	210.24	59.3	.593	124.67	12.27	35.00	429.45	0.29
1983	212.43	68.3	.683	145.09	12.41	35.00	434.35	0.33
1984	214.62	76.2	.762	163.54	12.54	35.00	438.90	0.37
1985	217.12	83.0	.830	180.21	12.68	35.00	443.80	0.41
1986	219.31	88.2	.882	193.43	12.82	35.00	448.70	0.43
1987	221.50	92.0	.920	203.78	12.96	35.00	453.60	0.45
1988	223.69	94.8	.948	212.06	13.09	35.00	458.15	0.46
1989	226.51	96.7	.967	219.04	13.23	35.00	463.05	0.47
1990	228.70	98.1	.981	224.35	13.37	35.00	467.95	0.48
1991	231.83	99.0	.990	229.52	13.50	35.00	472.50	0.49

*All dollar values are in 1973 dollars

burn fatalities (1.4 percent) and fire accidents derived in Section 2.1.1. If the higher estimates of burn fatalities (3.2 percent) and fire accidents are used in the analysis, the countermeasures system does become cost/beneficial on a yearly basis in 1987. The savings/cost ratio by 1991, using these higher estimates, would be 1.11. This amounts to a total savings of 50.2 million dollars or more per year thereafter.

5.6.3 Electrical Countermeasures System

This system would remove the majority of ignition sources (electrical sparks and lighted headlamp filaments) by utilizing an electrical system inertia cutoff switch and a shielded battery terminal. The cost of this countermeasures system was estimated at $3.00. This includes:

	Item	Cost
1.	Shielded Battery Terminal	$0.50
2.	Electrical Inertia Switch	2.50
		$3.00

This sytem was considered 85 percent effective in eliminating ignition sources since it would eliminate only electrical sources and not friction sparks or hot surfaces. However, the laboratory tests and literature survey showed that both of the latter ignition sources represented only a small hazard as compared to the electrical sources. Fiat researchers (Reference 13) could ignite gasoline with friction sparks in only 10 percent of the cases, even when dragging a car body longer distances over pavement than would normally occur during an accident where sheet metal might contact the pavement. Although all laboratory attempts at autoignition of gasoline from hot surfaces failed, there might be some instances where this could occur. Thus, subtracting 10 percent ignition by friction sparks and 5 percent by autoignition and miscellaneous sources, an effectiveness of 85 percent remained for the electrical countermeasures system.

When only the electrical countermeasures are added to the vehicle, the analysis must consider the probabilities of vehicles with and without countermeasures being involved in an accident. Three different probabilities were considered in arriving at an effectiveness factor for a given year: (1) the probability of a single vehicle with countermeasures being involved in an accident, (2) the probability of two vehicles with countermeasures being involved, and (3) the probability of two cars being involved when only one has countermeasures. After 15 years the effectiveness factor will be .839 and is approaching .850 which is the percent effectiveness which was assigned to this system.

The results of the analysis are shown in Table 5-9. The figures indicate that the savings with the countermeasures system would be greater than the total system costs per year within three years following the introduction of the system into all new vehicles. Moreover, the total cumulative savings after five years would exceed the total cumulative costs by 26.44 million dollars and would increase every year beyond that.

Since this analysis was based on minimum burn fatality and fire accident predictions, there is no doubt that the electrical countermeasures system is very cost effective. However, it should be remembered that this system will not eliminate all burn fatalities. The incalculable costs to the remaining burn victims and their families cannot be estimated nor valued.

TABLE 5-9. COST/BENEFIT ANALYSIS OF ELECTRICAL COUNTERMEASURES SYSTEM*

Year	Fire Cost Without System ($ Million)	Percent Vehicles With System	System Effectiveness Factor	Fire Savings With System ($ Million)	New Vehicles Registered (Million)	System Cost Per Vehicle ($)	Total Vehicle Costs ($ Million)	Savings/Cost Ratio (Per Year)
1976	198.98	0	0	0	11.45	0	0	0
1977	200.77	10.0	0.058	11.64	11.59	3.00	34.77	0.33
1978	202.42	20.0	0.122	24.70	11.72	3.00	35.16	0.70
1979	204.61	30.1	0.193	39.49	11.86	3.00	35.58	1.11
1980	206.49	40.0	0.269	55.55	11.99	3.00	35.97	1.54
1981	208.36	49.8	0.350	72.93	12.13	3.00	36.39	2.00
1982	210.24	59.3	0.429	90.19	12.27	3.00	36.81	2.45
1983	212.43	68.3	0.513	108.98	12.41	3.00	37.23	2.93
1984	214.62	76.2	0.592	127.06	12.54	3.00	37.62	3.38
1985	217.12	83.0	0.664	144.17	12.68	3.00	38.04	3.75
1986	219.31	88.2	0.717	157.25	12.82	3.00	38.46	4.09
1987	221.50	92.0	0.760	168.34	12.96	3.00	38.88	4.33
1988	223.69	94.8	0.793	177.39	13.09	3.00	39.27	4.52
1989	226.51	96.7	0.816	184.83	13.23	3.00	39.69	4.66
1990	228.70	98.1	0.827	189.13	13.37	3.00	40.11	4.72
1991	231.83	99.0	0.839	194.51	13.50	3.00	40.50	4.80

*All dollar values are in 1973 dollars

6.0 COUNTERMEASURE DEMONSTRATION TESTS

Four full-scale vehicle crash tests, as outlined in Table 6-1, were conducted to demonstrate the effectiveness of selected countermeasures for both ignition sources and spilled fuel. The test vehicles and test conditions were identical to those used during the baseline tests with the exception of the countermeasure systems incorporated in the vehicles. As noted in Section 4.0, the baseline test conditions provided both spilled fuel and ignition sources during the impact to ensure that a fire would result. In the demonstration test series, one of these sources, either fuel or ignition, was always available, and the second source was negated by the use of countermeasures. If the countermeasure system failed to operate, both sources would be available as in the baseline tests and a fire would occur.

TABLE 6-1. DEMONSTRATION CRASH TEST MATRIX

Test Type	Striking Car Configuration	Struck Car Configuration	Ignition Source Countermeasures	Fuel Spillage Countermeasures
Front-to-Rear	Front Engine	Rear Fuel Tank	Yes	No
Front-to-Rear	Front Engine	Rear Fuel Tank	No	Yes
Rollover	Front Engine, Rear Fuel Tank	NA	Yes	Yes
Front Barrier	Front Engine	NA	Yes	No

6.1 TEST EQUIPMENT

The demonstration test series utilized the same test equipment to produce ignition sources and fuel spillage as was used during the baseline tests. This equipment included the spark igniter package, fuel spray system, fuel tank ram, bumper plates, and barrier fuel pan described in Section 4.1.

Unlike the baseline tests, acceleration of the demonstration test vehicles was monitored and recorded. The accelerometer locations are specified in Figure 6-1. Inertia switch and spark igniter relay actuation times were also monitored and recorded. Additional data were obtained from high-speed motion pictures.

All of the test vehicles were 1971 Plymouth Fury sedans. As in the baseline tests, the striking car in the first front-to-rear test was used as the struck car in the second front-to-rear test.

6.2 COUNTERMEASURE SYSTEMS TESTED

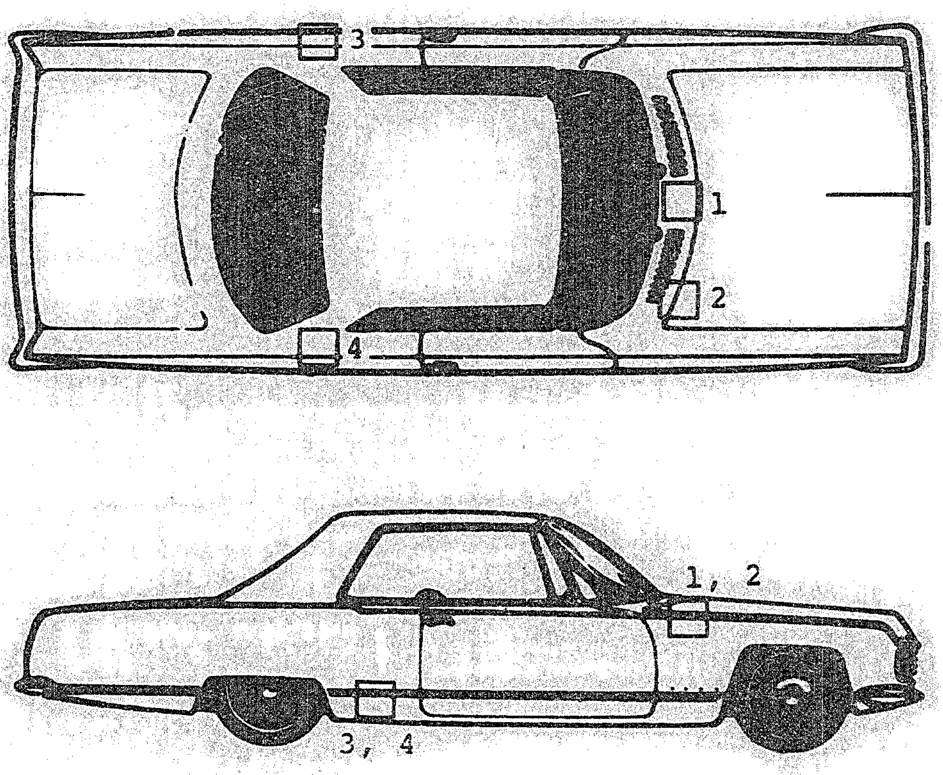
Detailed descriptions of the countermeasures selected for the demonstration tests and the criteria used in their selection were described in Section 5.5. The following paragraphs describe the installation of the countermeasures in the demonstration vehicles.

6.2.1 Fuel System Countermeasures

The first front-to-rear test and the rollover test incorporated fuel system countermeasures. Both systems were identical with the following exception. The front-to-rear impact used a fuel cell manufactured by Fuel Safe Corporation while the rollover test used a tank manufactured by Aero Tec Laboratories (ATL). The rollover test also used a carburetor rollover valve.

The vehicles were modified by removing the existing vehicle fuel tanks and replacing them with the safety fuel tanks which were installed above the rear axle in the trunk. This location provided additional vehicle crush area behind the fuel tank. The tank from Fuel Safe Corporation was mounted in a light aluminum box since, without foam, the tank is not freestanding.

A filler plate, manufactured by Aero Tec Laboratories, was mounted in the top of both tanks. This plate included a 2-1/4-inch filler pipe, two return lines, one outlet line, and one vent line. The filler pipe contained a flapper valve to stop fuel flow during a rollover or due to hydraulic ram pressure when the tank was crushed. All remaining fittings on the plate consisted of 37-degree AN flare fittings.



Location 1: Triaxial accelerometer on all tests. Located on vehicle firewall at the vehicle centerline.

Location 2: Longitudinal accelerometer on front-to-rear and barrier tests and triaxial accelerometer on rollover test. Located 12 inches to the right of vehicle centerline on the firewall.

Location 3: Longitudinal accelerometer on front-to-rear and barrier tests. Located on the vehicle left frame 12 inches forward of the rear wheel well.

Location 4: Longitudinal accelerometer on front-to-rear and barrier tests. Located on the vehicle right frame 12 inches forward of the rear wheel well.

Figure 6-1. Accelerometer Locations for Demonstration Tests.

The filler cap was installed near the top of the left rear quarter panel by the "C" pillar. The filler line to the tank was composed of 2-inch-diameter rubber hose held in place with hose clamps.

The fuel line was made from steel tubing which was routed down through the trunk floor and connected to the main fuel line with a short piece of rubber hose and hose clamps. The vent line was routed to a liquid-vapor check valve which was manufactured for American Motors cars. This valve was mounted on the rear sheet steel firewall which had been added for occupant protection. From this location, the line was run down through the wheel well to the existing vent line. The vent system was totally plumbed with rubber line due to hose-type fittings on the liquid-vapor check valve.

A rollover carburetor shutoff valve was installed for the rollover test. Although an electrical system shutoff switch installed in the vehicle would eliminate ignition sources, it was desirable to test the carburetor rollover valve for a complete assessment of fuel spillage countermeasures.

The fuel tanks were filled to 90-percent capacity for the demonstration tests to assure that the worst case for spillage would be present. This also presented the worst case from the standpoint of hydraulic pressure developed from crush or head pressure on the check valves in a rollover.

Figures 6-2 through 6-5 show the fuel system countermeasures as installed for the demonstration tests.

6.2.2 Electrical System Countermeasures

Electrical system countermeasures were utilized during the second front-to-rear test and the barrier and rollover tests. The countermeasure system installation was the same for each test. Two inertia switches from Inertia Switch, Ltd. were used. A type 3566 (see Table 5-3) was used to remove the main battery power from the vehicle. This unit was set to operate at 5.5G. A second switch, type 3562, was used in the battery lead to the alternator

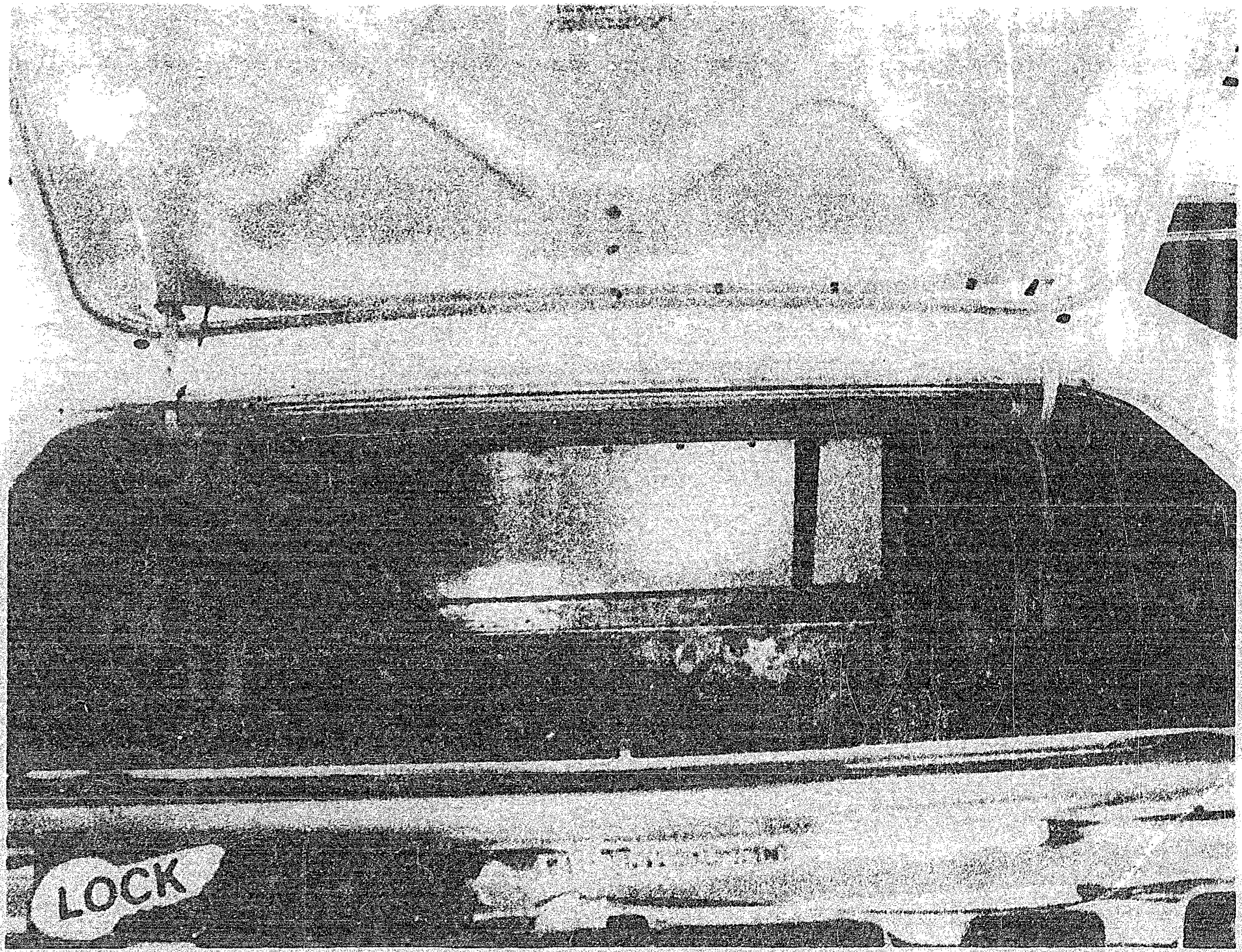


Figure 6-2. Fuel Cell and Spark Igniters for First Front-to-Rear Test.

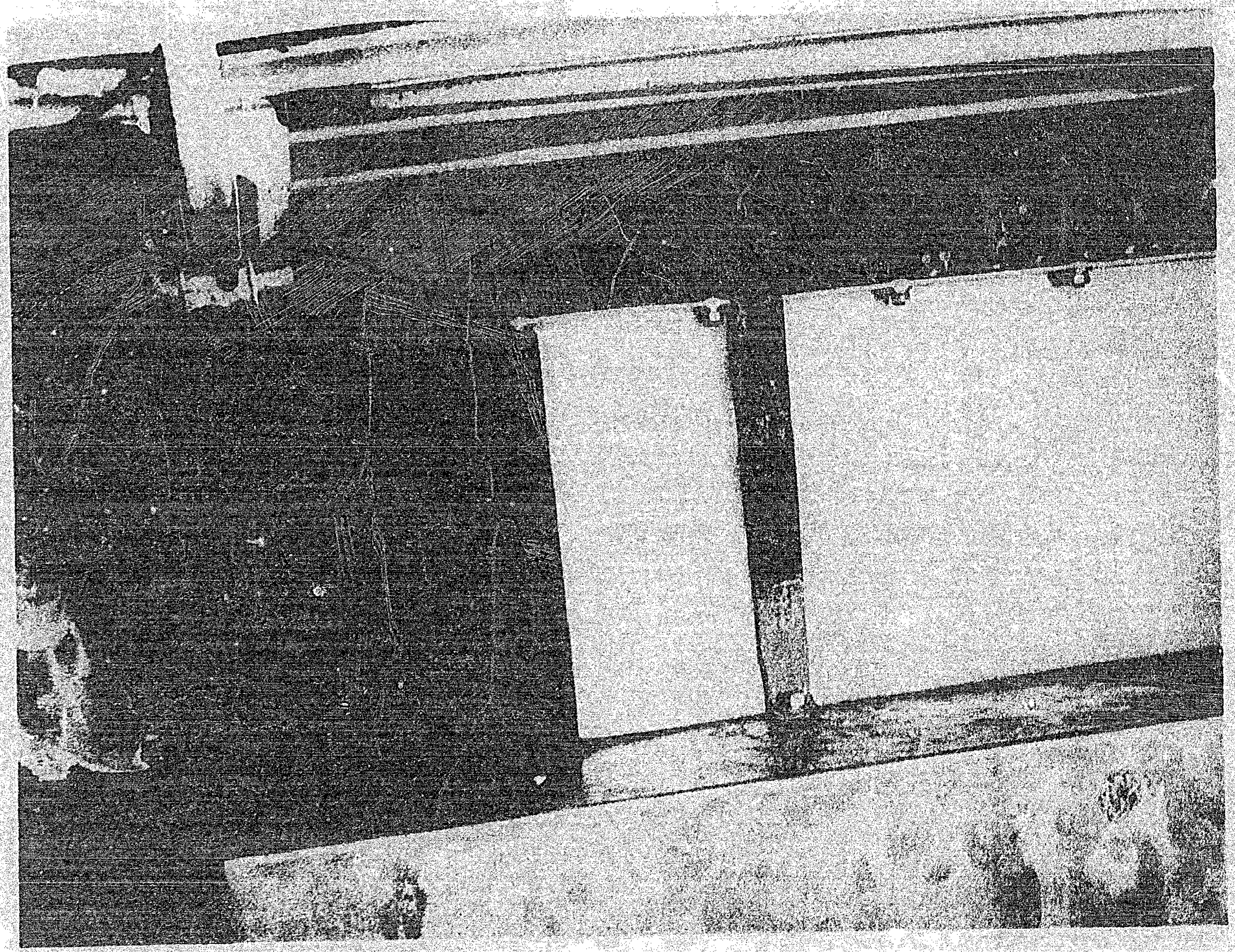


Figure 6-3. Fuel Cell and Attaching Lines Installation for First Front-to-Rear Test.

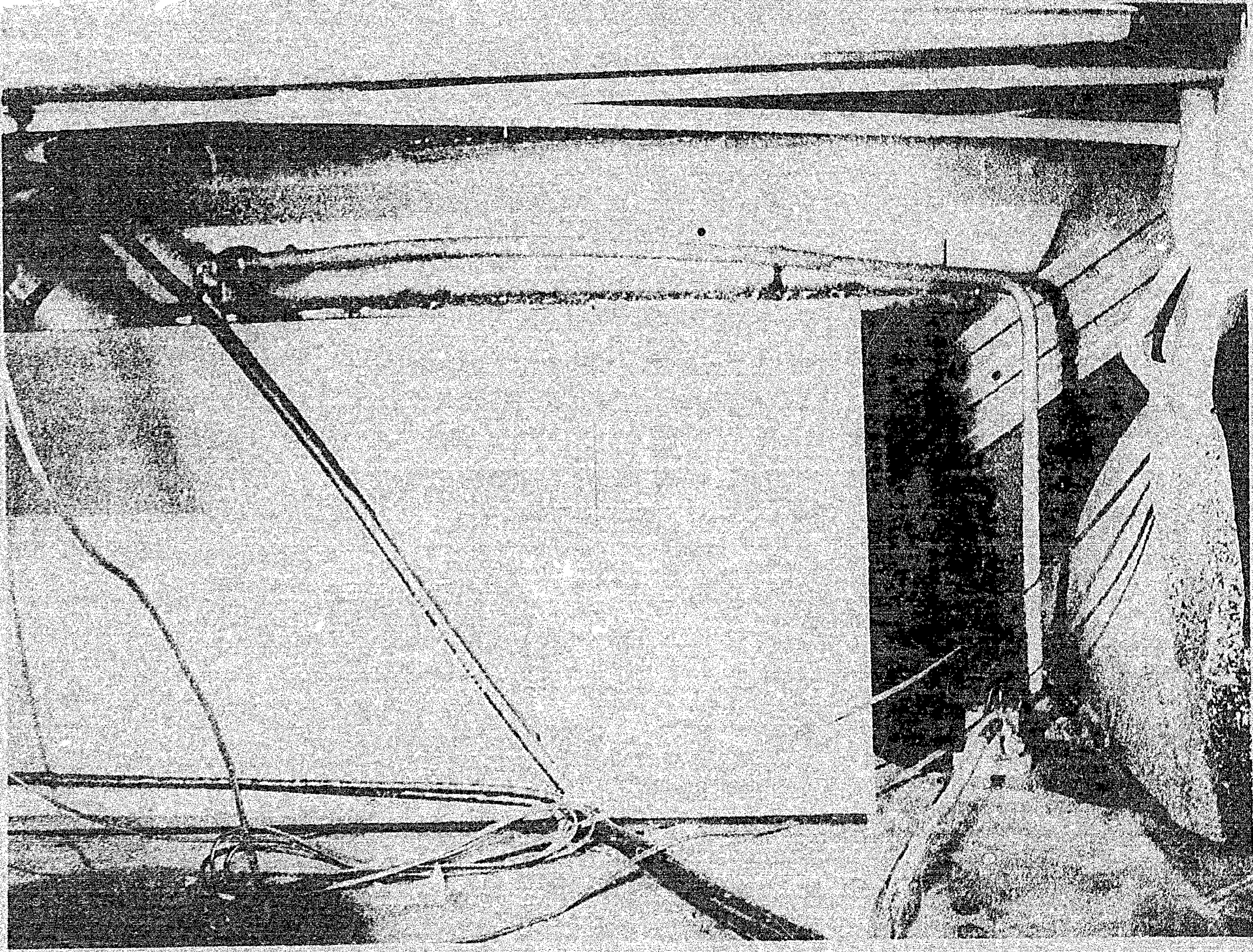


Figure 6-4. Fuel Cell and Spark Igniter Installation for Rollover Test.

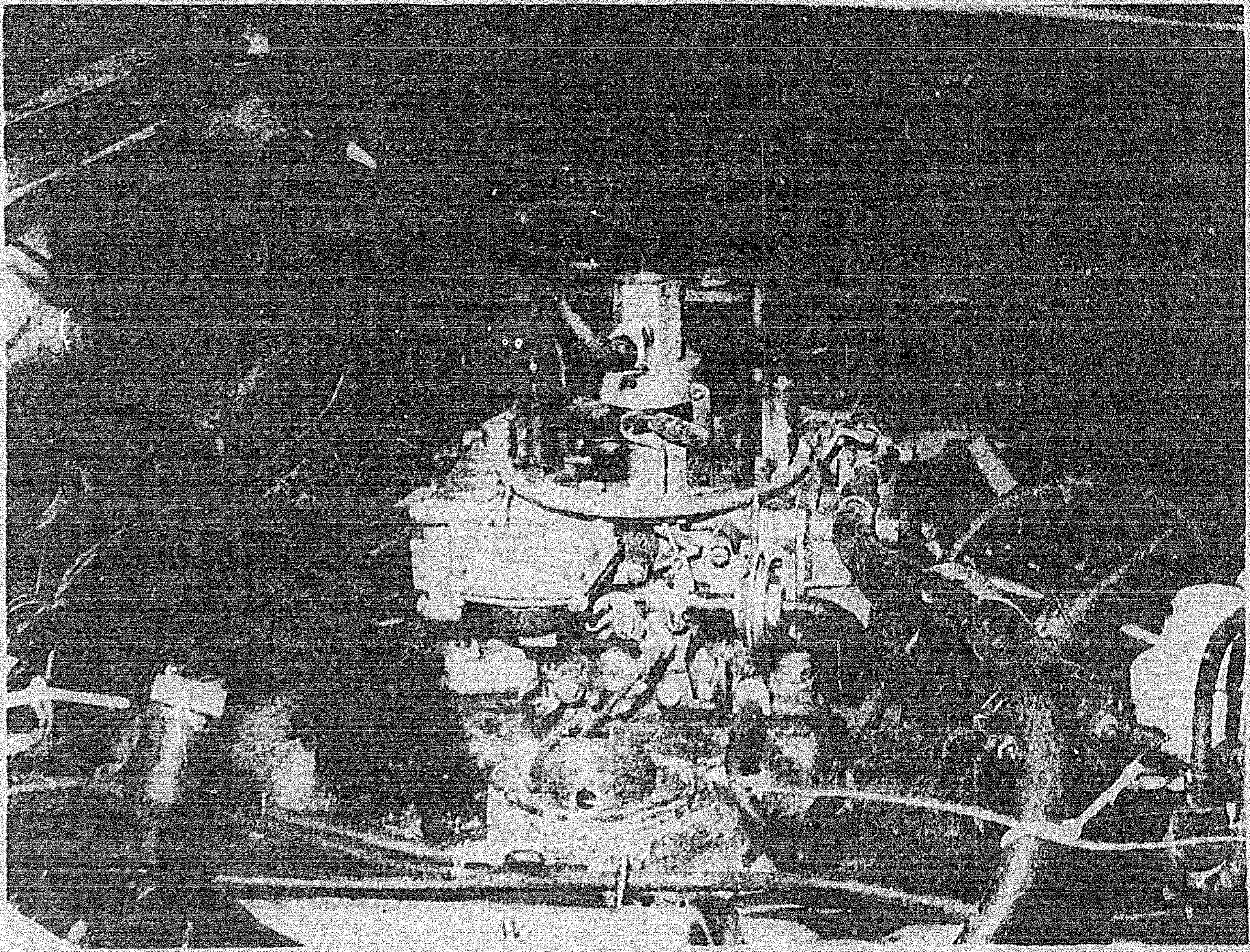


Figure 6-5. Rollover Valve Installed on Carburetor for Rollover Test.

to prevent the engine from running after the impact. (A single switch mechanism, which was ordered from Inertia Switch, Ltd., performed both of these functions, but it was not available in time for testing.) In addition to the shutoff switches, the battery terminal was protected by a plastic/aluminum terminal protector fabricated by Ultrasystems. Figures 6-6 and 6-7 show the installation of the electrical countermeasures.

6.3 TEST CONDUCT AND RESULTS

6.3.1 Barrier Test

The barrier test was a 30-mph impact into a flat barrier over pooled fuel. This test duplicated the conditions used in the baseline tests.

The vehicle was modified to accommodate the electrical countermeasure system and the spark igniter package. The spark sources were placed as shown in Figure 4-4, the same locations as in the baseline test.

The fuel system was drained completely and the fuel tank was filled with water. An auxiliary fuel tank was installed at the rear of the vehicle to provide sufficient fuel for engine operation throughout impact. Accelerometers were installed as shown in Figure 6-1.

The engine was started and run for 15 minutes just prior to the test to permit it to reach normal operating temperature. When the vehicle was ready, 7 gallons of fuel were added to the barrier pan. The test vehicle was then towed into the barrier with its engine still running. The impact velocity was 29.72 mph.

The electrical inerting system functioned properly and totally shut down the vehicle electrical system and engine 10 msec after impact with the barrier. At this time, 5.0 inches of a total 24.3 inches of crush had occurred. The spark igniter switch actuated 48 msec after impact, but there was no fire since the igniters depended on power from the vehicle's electrical system which had already been inerted. If the inerting system had not operated, a fire would have resulted shortly after this time.

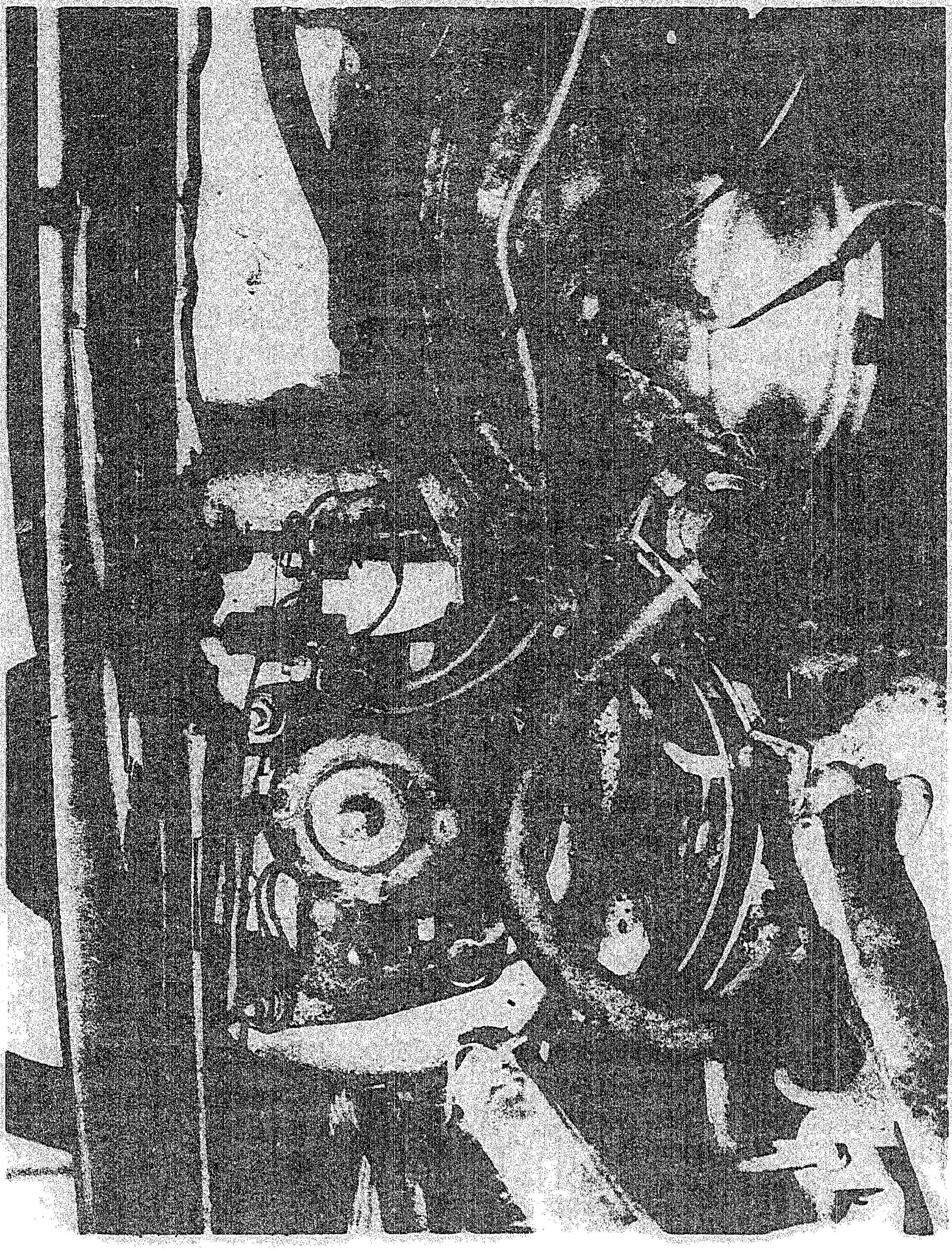


Figure 6-6. Typical Inertia Switch Installation.

Figure 6-7. Typical Battery Terminal Shield Installation.

An electrical short did occur in some instrumentation wiring that was monitoring the vehicle inertia switch actuation. The insulation on the wire was melted off, but the wire was located well away from the available fuel source. This wiring was not protected by the inertia switch since it was not part of the vehicle's electrical system.

Figure 6-8 shows the damage experienced by the vehicle. The firewall longitudinal acceleration is shown in Figure 6-9. (Refer to the Appendix for remaining frame and firewall acceleration data.) Figure 6-9 indicates that, since the inertia switch actuated 10 msec after impact, the electrical system was totally inerted when the deceleration level reached 20G and a velocity change of only 2.5 feet/second had occurred.

6.3.2 Fuel System Countermeasures Front-to-Rear Test

The first front-to-rear impact was a test of the fuel countermeasures system under a severe (60-mph) rear impact condition.

The struck vehicle was modified with the relocated safety fuel tank and associated countermeasures as described in Section 6.2.1. The struck vehicle was also equipped with the spark igniter package and the fuel tank ram and bumper plates used in the baseline tests. The ram and bumper plates were in the same location as on the baseline tests so the same crush conditions were encountered even though the tank had been relocated. The igniters were relocated near the safety tank as shown in Figures 6-2 and 6-3. The safety fuel tank was filled to 90 percent of its capacity with gasoline.

The striking vehicle was equipped with an onboard abort system which applied the vehicle's brakes 0.5 second after impact. No other modifications were made to the vehicle.

The impact velocity of the striking vehicle was 60.60 mph. The spark igniter system began operation 187 msec after impact and continued for a minimum of 30 seconds. This provided more than adequate time to ignite all but minimal fuel spillage but no fire occurred. Figures 6-10 and 6-11 show the post-test vehicle

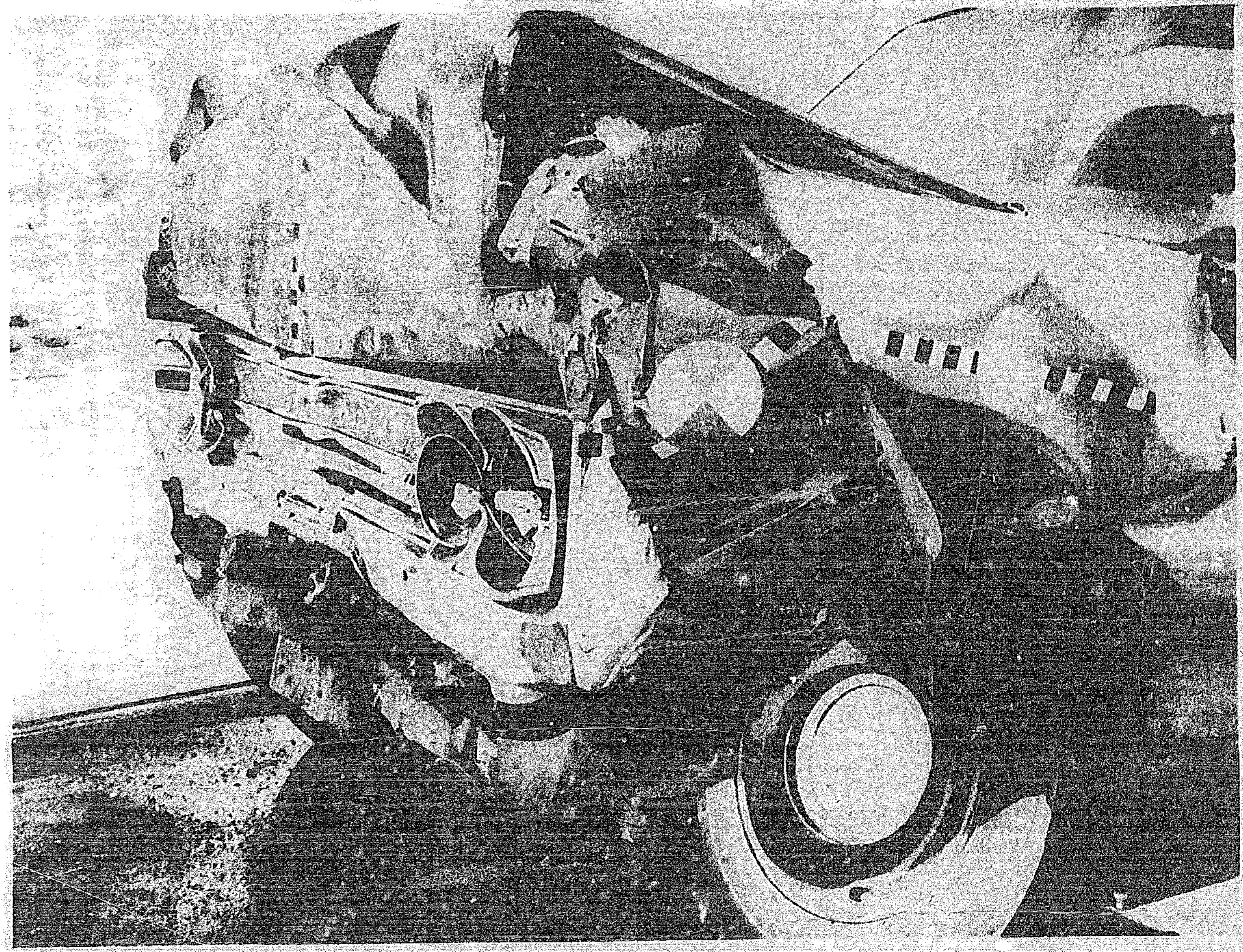


Figure 6-8. Damage to Demonstration Barrier Test Vehicle.

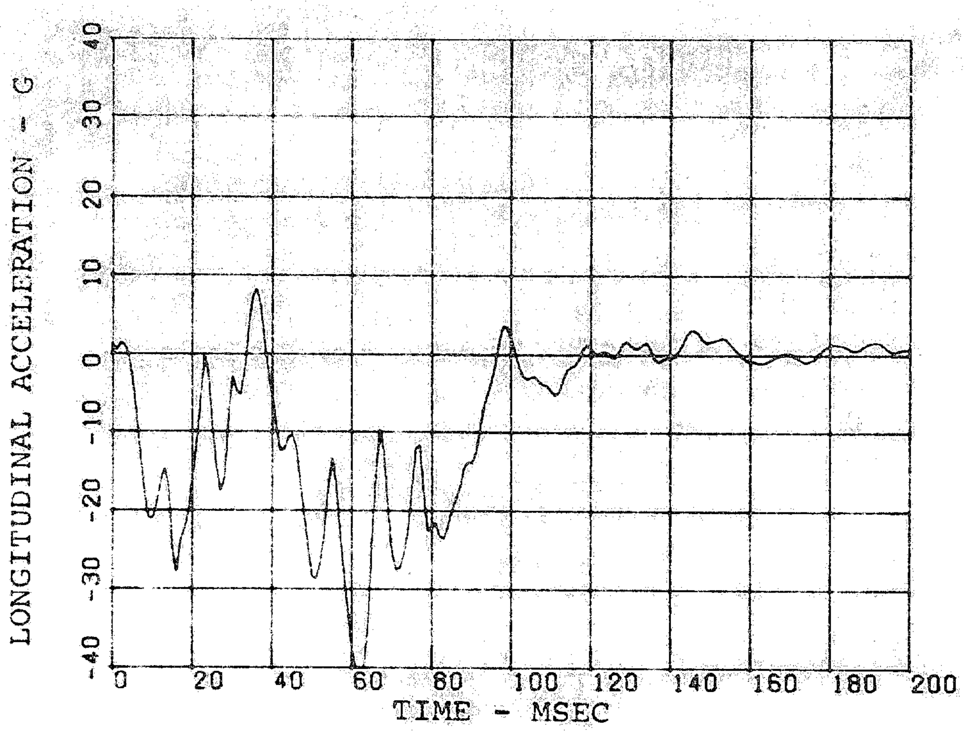


Figure 6-9. Firewall Acceleration of Demonstration Barrier Test Vehicle (Location 2).

damage. The fluid in the foreground of Figure 6-10 is water washdown to assure that the area was safe since a small leak did develop in the vent system.

The fuel vent line which ran from the liquid-vapor check valve to the engine valve cover was sheared off where it passed through the trunk floor. This posed no problem since the valve was float-operated and any fuel would be shut off by the float system. However, a minor leak did occur in the valve area. The exact location of the leak was totally masked from view by metal deformation. The reason for the leak was never determined. By the time the tank was emptied and metal removed, all signs of any leak had disappeared. It is felt that the leak occurred from the valve, but definite proof was never found. Tank pressure was recorded during the test to determine the hydraulic pressure resulting from the impact. A short duration pulse of 300 psi was observed approximately 130 msec after impact. This surge may have caused the leak.

Figure 6-10. Post-test View of First Front-to-Rear Demonstration Test.

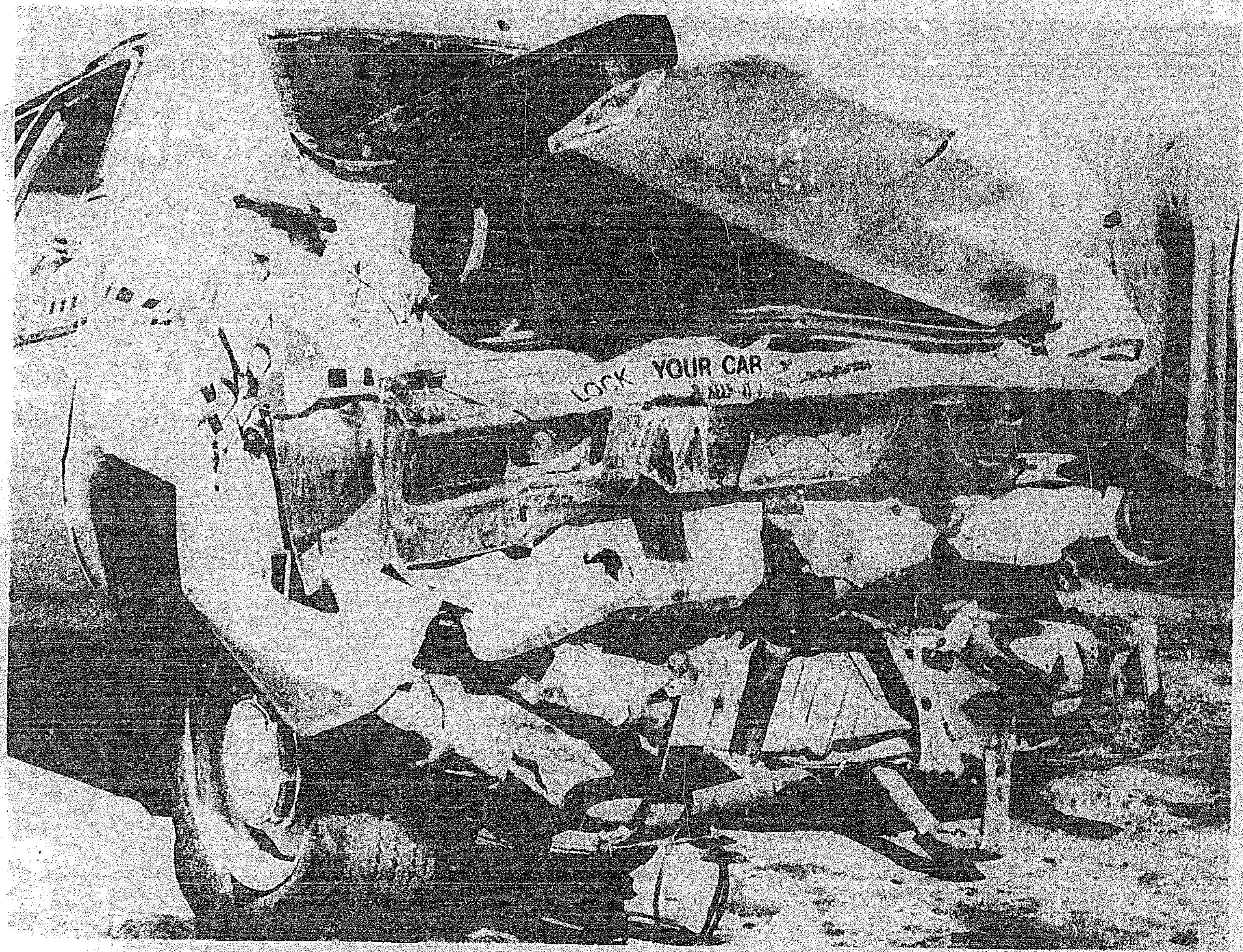


Figure 6-11. Struck Car Damage From First Front-to-Rear Demonstration Test.

After the safety fuel tank had been removed from the car, it was carefully inspected for leaks and was found to be in perfect condition although it had been subjected to severe impact forces. Figure 6-12 shows how the tank was crushed inward and displaced upward during the crash while Figure 6-13 shows the inward deformation of the rear firewall caused by the tank being pushed forward.

A total dynamic crush of 42.2 inches occurred 87 msec after impact. Figure 6-14 shows the acceleration pulse experienced by the vehicle at the firewall. This pulse was very similar to that seen on the frame just forward of the rear wheel well shown in Figure 6-15. The remainder of the acceleration data and the tank pressure data are located in the Appendix.

6.3.3 Electrical System Countermeasures Front-to-Rear Test

The second 60-mph front-to-rear impact was a test of the electrical system countermeasures. The striking car was equipped with the electrical system inertia switches and battery terminal shield as described in Section 6.2.2.

The struck vehicle was equipped with a fuel tank ram (as in the baseline front-to-rear tests), and the fuel tank was filled to 90 percent of its capacity with gasoline. The striking vehicle was equipped with the spark igniter package and the fuel spray system as shown for the baseline tests in Figure 4-14. This system was connected through the main vehicle electrical system. The fuel tank was drained and an auxiliary tank was mounted at the rear of the striking vehicle to supply fuel for engine operation during the test. The engine was started and allowed to idle for 10 minutes before the test so that operating temperatures would be reached. The engine was running at impact.

The striking car struck the rear of the stationary car at 59.61 mph. The fuel tank on the struck vehicle was ruptured on impact and sprayed fuel over a large area. The electrical inertia switches on the striking vehicle actuated 18 msec after impact when 4.5 inches of a total 42.8 inches of struck vehicle

Figure 6-12. Post-test Fuel Tank Crush From First Front-to-Rear Demonstration Test.

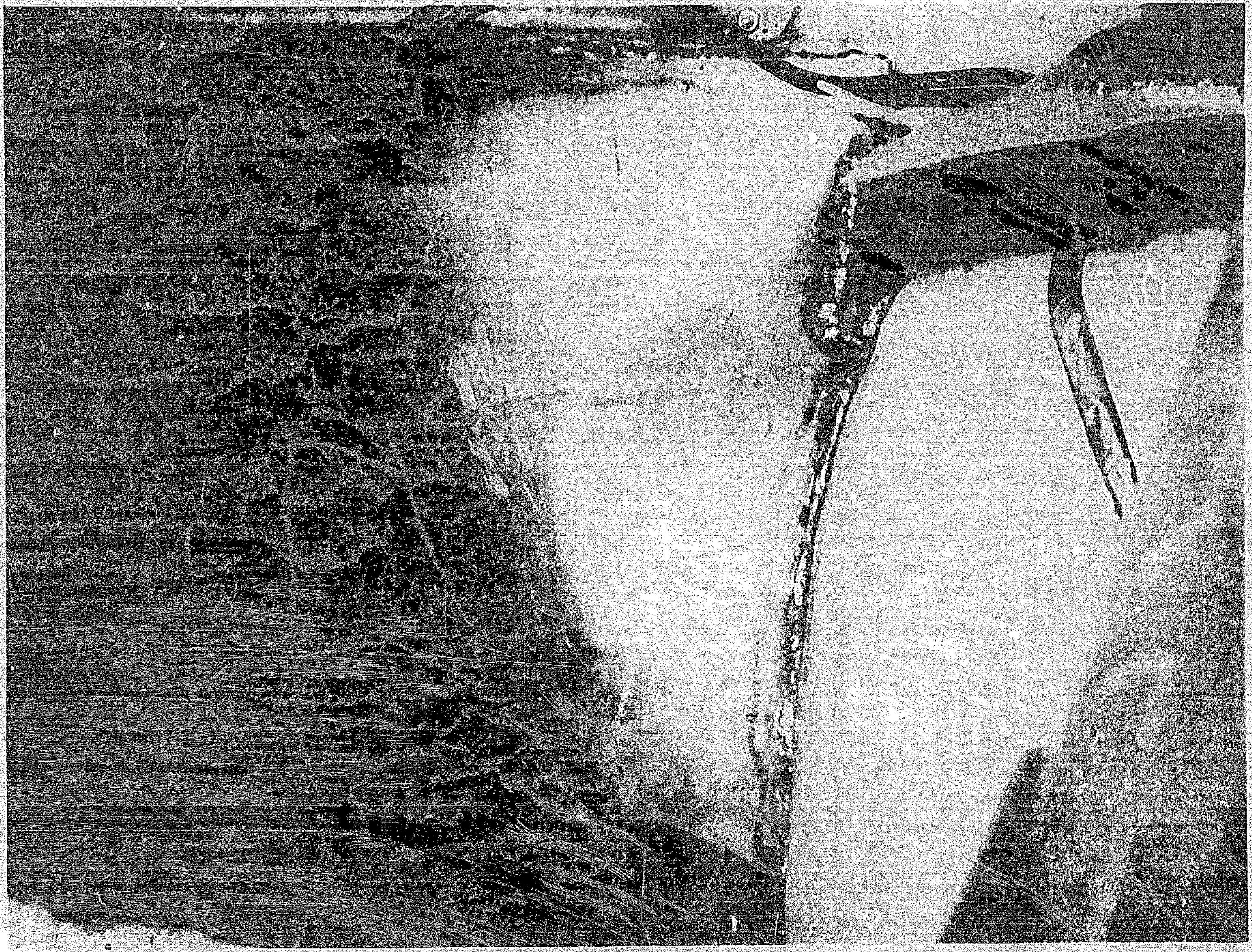


Figure 6-13. Inward Deformation of Rear Firewall Caused by Fuel Tank Crush During First Front-to-Rear Demonstration Test.

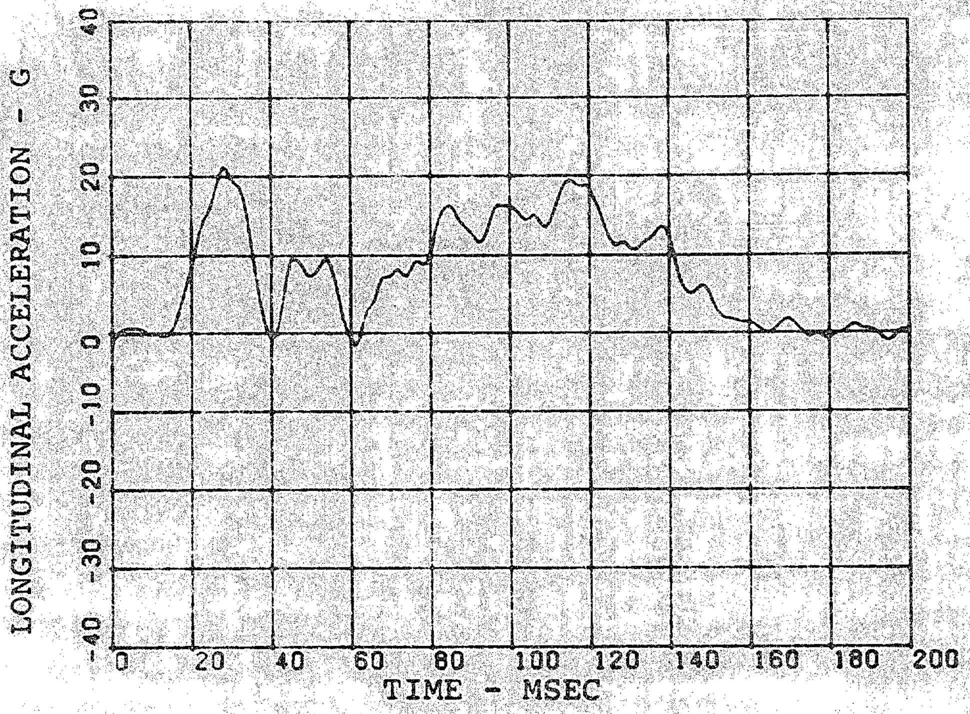


Figure 6-14. Firewall Acceleration of Struck Vehicle During First Front-to-Rear Test.

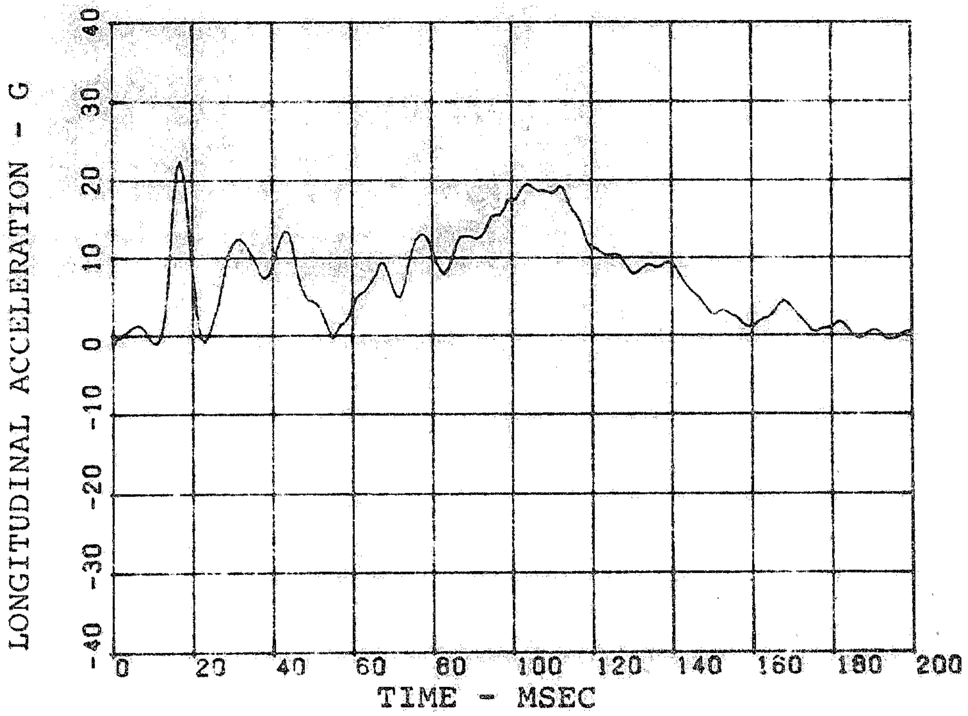


Figure 6-15. Frame Acceleration of Struck Vehicle During First Front-to-Rear Test.

crush had occurred. At this point, all electrical ignition sources, including the spark igniters, were rendered safe and the spilled fuel did not ignite.

Figure 6-16 shows the damage received by the striking car while Figure 6-17 shows the damage received by the struck vehicle. The area had been washed down after the test to remove the gasoline.

Figure 6-18 shows the deceleration levels encountered on the engine firewall of the striking vehicle. The inertia switches actuated when the acceleration reached 17G (18 msec) and the velocity had changed 2.5 feet/second. These results are quite comparable to those obtained during the barrier test. Additional data traces are located in the Appendix.

6.3.4 Rollover Test

The rollover test was designed to test both the electrical and fuel system countermeasures. These countermeasures and their installation were described in Sections 6.2.1 and 6.2.2. The target velocity for this test was 30 mph.

The spark igniter package and fuel spray system were installed similarly to that of the baseline tests (Figure 4-17). The safety fuel tank was filled to 90 percent of its capacity with gasoline and the carburetor and fuel lines contained their normal amount of fuel. The test vehicle was then mounted on the rollover dolly as shown in Figure 6-19. When the vehicle was ready for test, the dolly was accelerated to the test speed and was released just prior to impact with the honeycomb snubber. The impact velocity was 29.08 mph.

The vehicle left the rollover dolly and landed on its right front and rear wheels and skidded on the tires. The vehicle failed to roll over although this test was run under the same conditions as the baseline test where the vehicle rotated 226 degrees. Post-test analysis revealed that the following items inhibited the roll: (1) The skid number of the pad was below

Figure 6-16. Striking Car Damage From Second Front-to-Rear Demonstration Test.

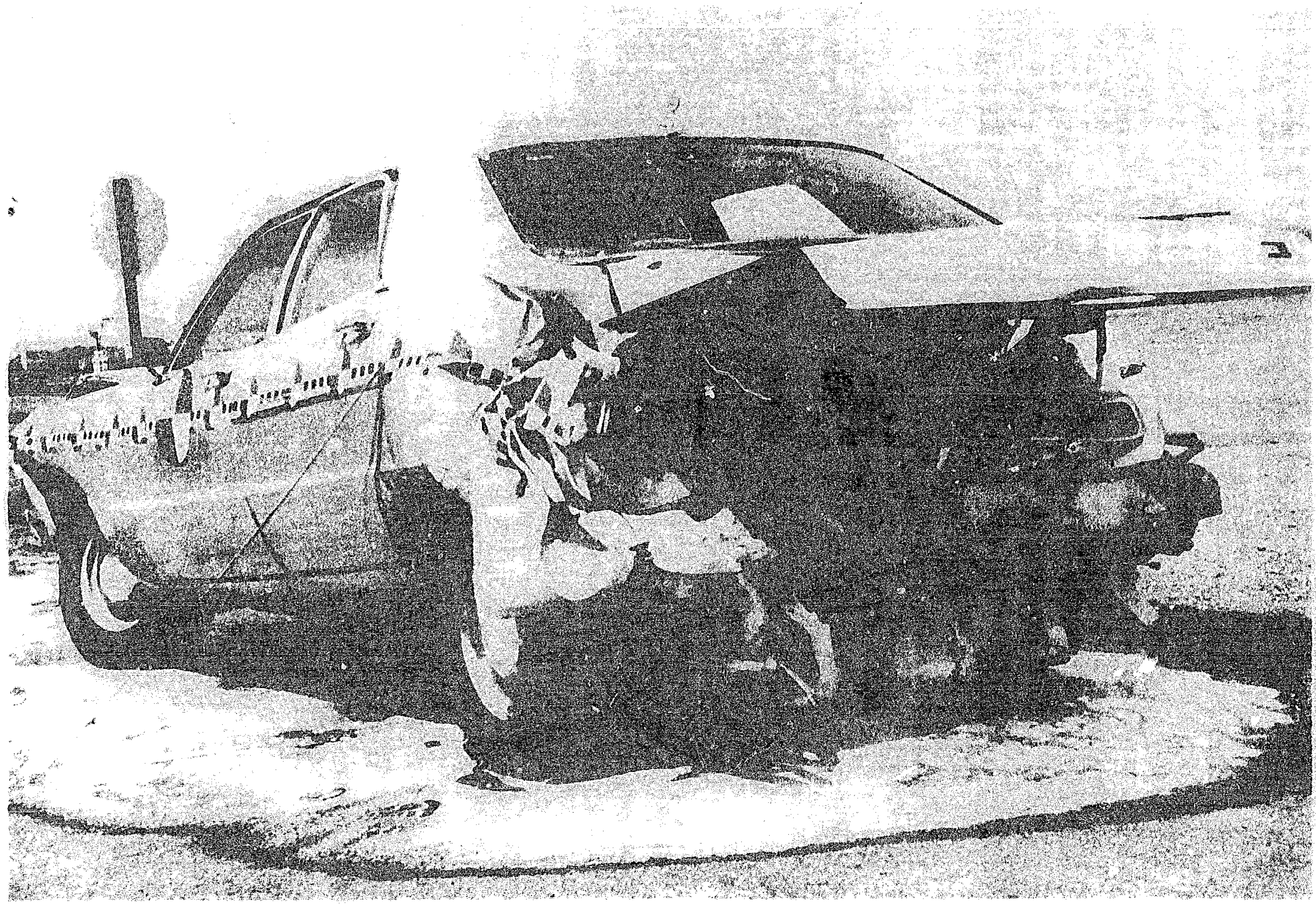


Figure 6-17. Struck Car Damage From Second Front-to-Rear Demonstration Test.

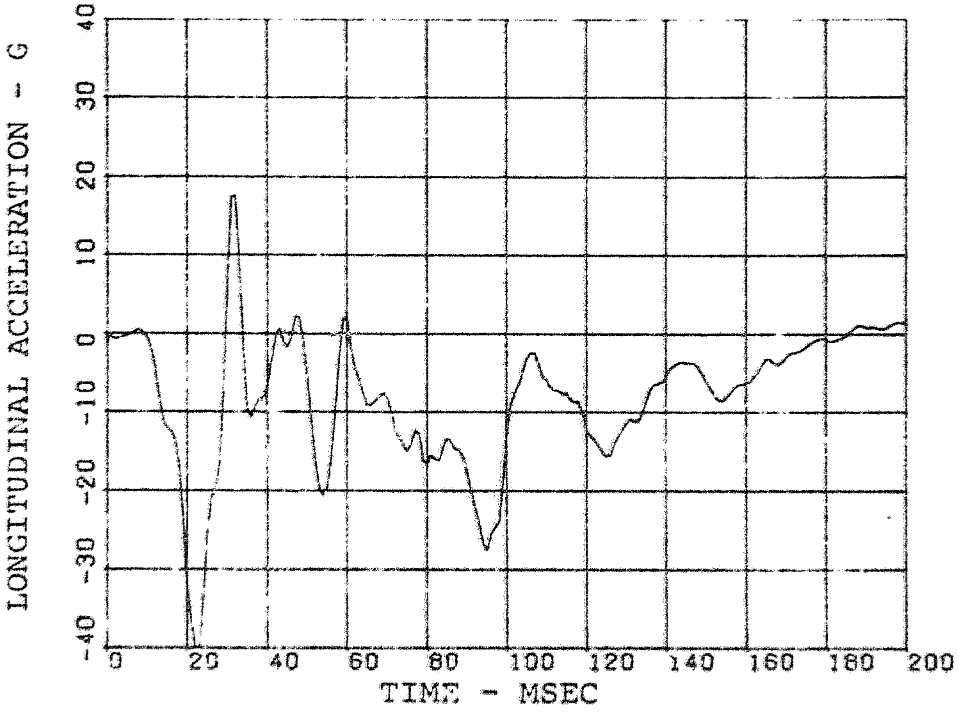


Figure 6-18. Firewall Acceleration of Striking Vehicle During Second Front-to-Rear Test.

that required for this type of test; (2) the tire pressure, although it was at a pressure for driving speeds (28 psi), was felt to be too low to initiate a good rollover; (3) the umbilical cable which was fastened to the front end of the car did not play out as anticipated and thus placed an additional load in a position below the vehicle's center of gravity.

To correct these problems, the following steps were taken: (1) The skid number on the rollover pad was increased by acid etching the surface; (2) the vehicle tires which were on the low side of the rollover dolly were pressurized to 50 psig. This allowed less deflection of the tires and permitted the car to rotate further before it left the dolly. (3) The umbilical cable was removed from the vehicle and an additional backup telemetry transmitter and antenna were added to the vehicle to transmit data.

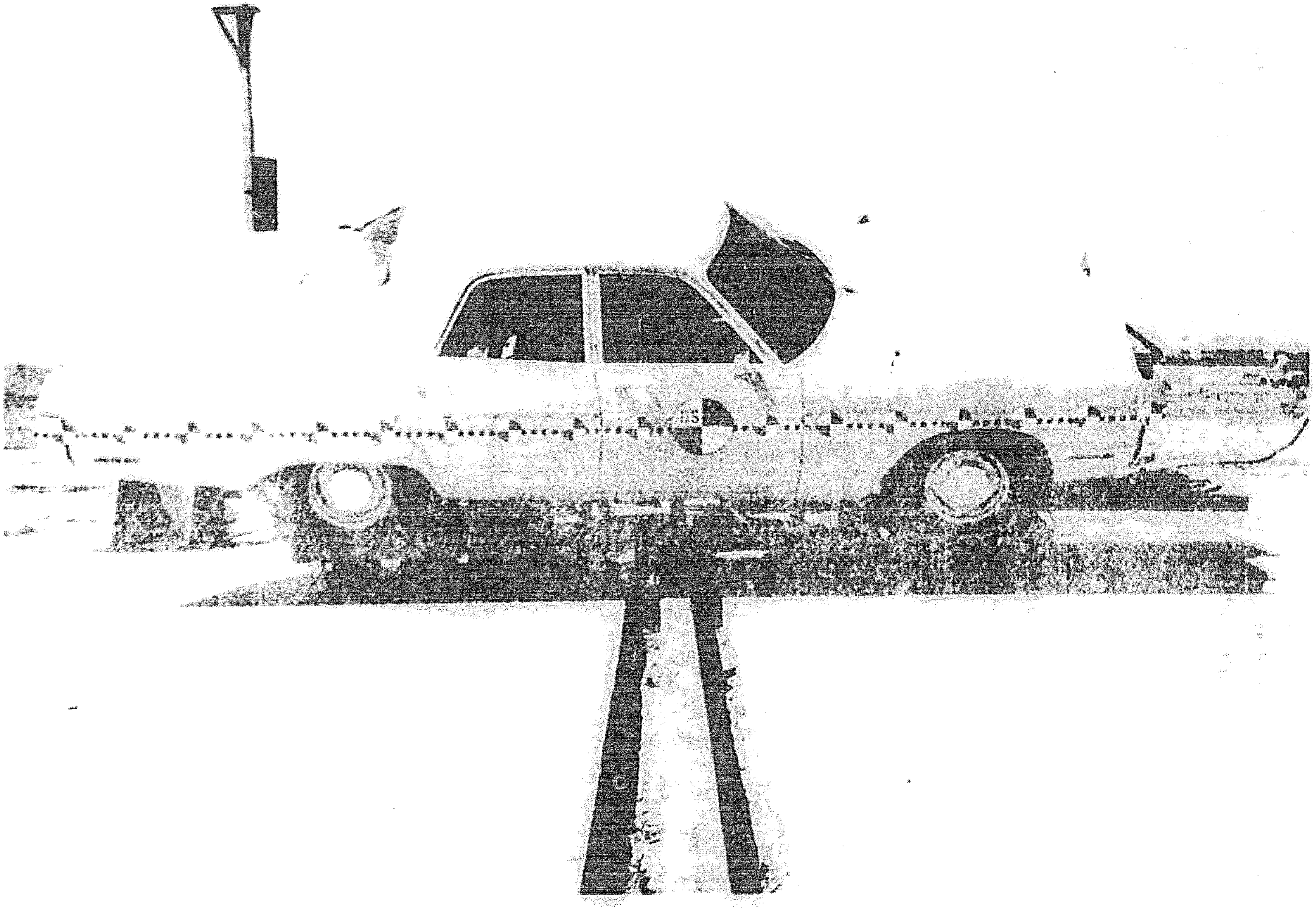


Figure 6-19. Demonstration Test Vehicle Mounted on Rollover Dolly.

The second rollover test was conducted at 32.77 mph. Upon leaving the dolly, the vehicle rolled one and a half times. Skid marks on the pad indicated the vehicle skidded 8 feet with probably 50 percent of that being wheel drag after the vehicle had started its roll. The exact time of inertia switch operation was lost due to an instrumentation failure. However, observation of the lighted headlamps on the high-speed movie film showed that the electrical system was inerted within 750 msec after the vehicle left the dolly. The spark igniter relay actuated 1,110 msec after the vehicle left the dolly and would have turned on the igniters if the electrical system had not been inerted. The vehicle came to rest on its roof 2.8 seconds after leaving the dolly as shown in Figure 6-20. There was no fire and no signs of fuel spillage from any part of the fuel system including the carburetor.

The demonstration rollover test was more severe than the baseline rollover test due to its higher impact speed and less energy loss due to tire skidding prior to the roll. Therefore, this additional energy resulted in more damage to the demonstration vehicle than to the baseline vehicle. Figure 6-21 compares these two test vehicles. However, the countermeasure system was completely successful even under these more severe conditions.

Figure 6-22 shows the resultant triaxial acceleration on the firewall. The inertia switches probably actuated 335 to 350 msec after the dolly impact during the well defined 9-10G acceleration pulse occurring at this time. This pulse was comprised mainly of lateral accelerations resulting from the right side of the vehicle contacting the ground. The remaining data traces may be found in the Appendix.

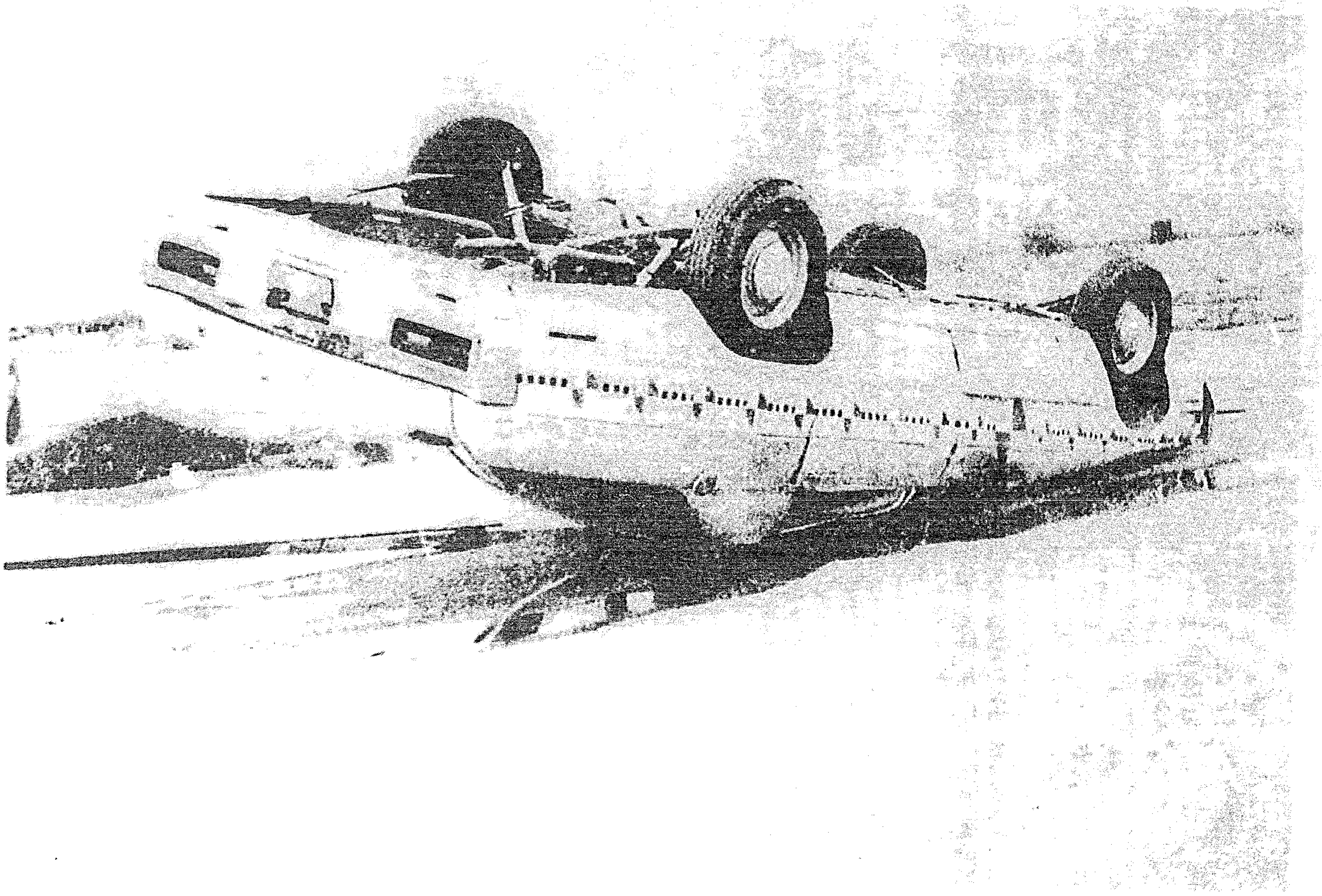


Figure 6-20. Post-test Position of Demonstration Rollover Vehicle.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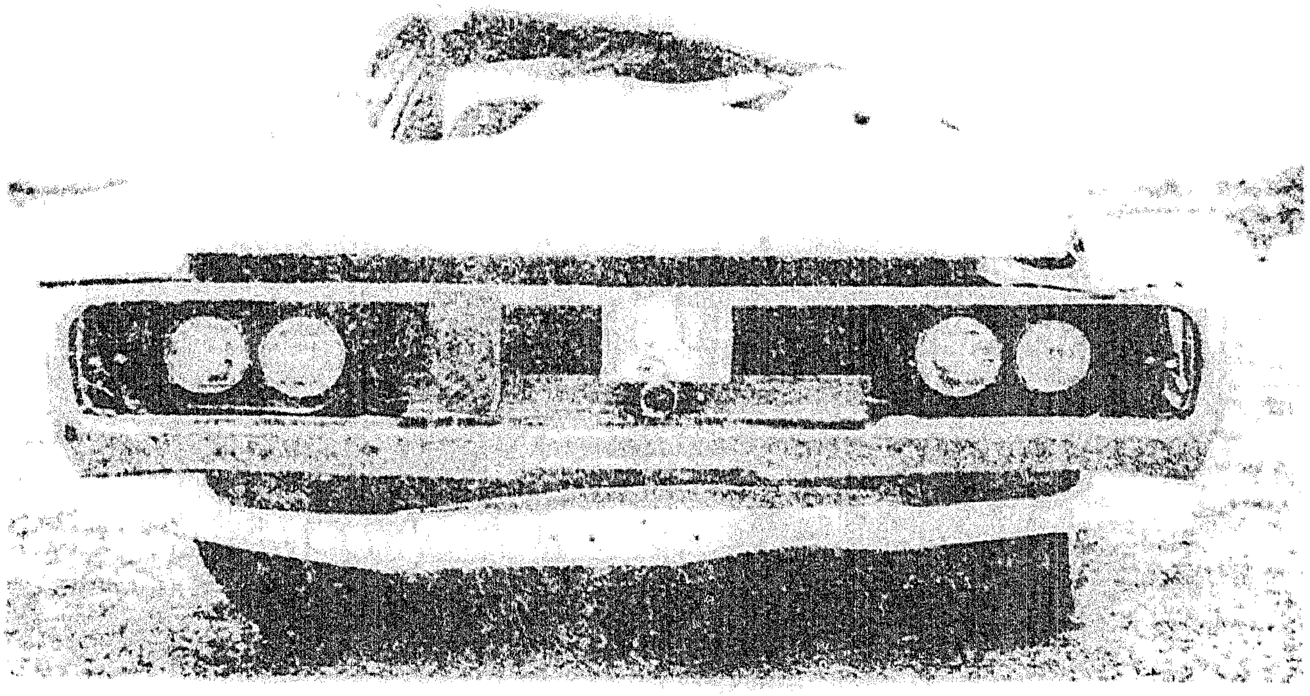

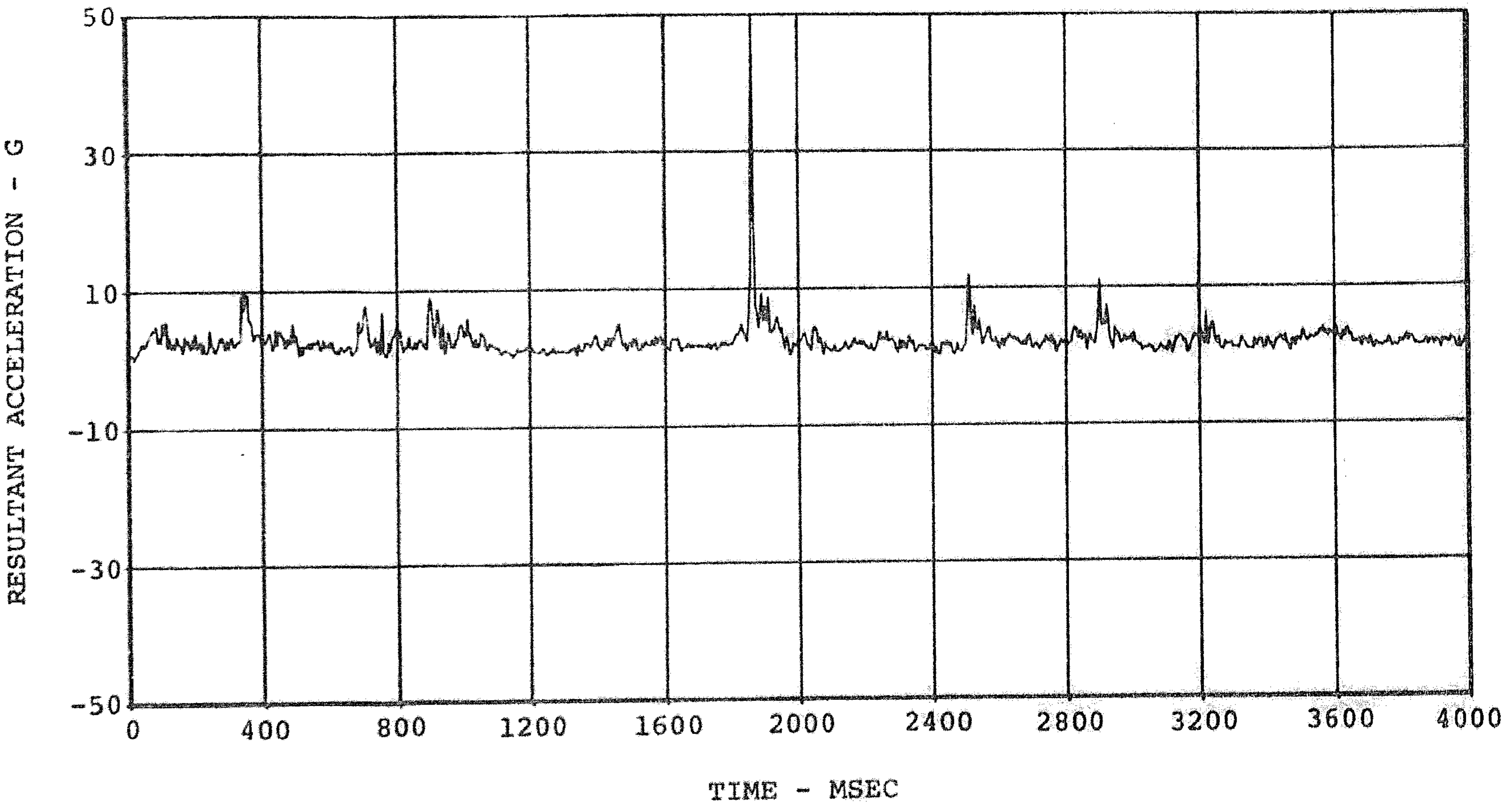

Figure 6-22. Resultant Firewall Acceleration During Demonstration Rollover Test.

7.0 SUMMARY AND CONCLUSIONS

This program consisted of basic research to define the conditions under which motor vehicle crash fires are ignited and the development of practicable countermeasures to reduce the incidence of these fires. The program was successful in that practicable countermeasures were developed for both ignition sources and fuel spillage. The effectiveness of these countermeasures was conclusively demonstrated during four full-scale crash tests. The following paragraphs summarize the major conclusions resulting from this study.

7.1 FIRE ACCIDENT STATISTICS

Fire accident statistics are both meager and inconsistent. Based on the results of available statistics, estimated nationwide 1972 motor vehicle fatalities occurring as a direct result of burns range from 625 to 1,430. The estimated number of nationwide fire accidents during 1972 range from 5,000 to 10,000.

7.2 IGNITION SOURCES

Based on the laboratory testing, electrical sources appear to be the most hazardous ignition sources. However, not all electrical components are hazardous. Those which are effective ignition sources include:

1. Direct battery shorts occurring either from sheet metal contact with the positive battery terminal or breaking and grounding of a hot wire in low-energy circuits.
2. Shorts occurring from the breaking and grounding of spark plug wires while the engine is running.
3. Inductive sparks produced by breaking the wire from the air conditioner compressor.

Vehicle headlights present a very definite ignition hazard. Headlamp filaments survive intact at a surprising rate and may continue to burn for 30 seconds or more after the glass is broken.

Friction sparks do not appear to pose as significant a fire threat as electrical ignition sources, although they are undoubtedly responsible for some crash fires.

The heated surfaces in a vehicle represent a low ignition hazard in a primary mode because of the rapid evaporation of gasoline. However, heated surfaces represent a hazard in a secondary mode since they provide vaporized gasoline to areas where effective electrical ignition sources may be present.

7.3 FUEL SYSTEM COUNTERMEASURES

Some safety fuel tanks which are currently being commercially manufactured will survive a 60 mph rear-end crash if they are mounted above the rear axle of the vehicle. A centrally located filler plate in these tanks contains the filler pipe opening, fuel outlet and return line fittings, and a vent line fitting. The use of a flapper valve in the filler opening, a flexible filler tube, a vent line check valve, and careful routing of a steel fuel outlet line, in addition to the safety tank, would successfully prevent all fuel spillage during a 60-mph rear-end impact.

Fuel spillage from the carburetor may be prevented during a rollover by incorporation of a ball-type check valve in the carburetor float bowl vent line. However, there is no commercially available valve at present for this application.

7.4 IGNITION SOURCE COUNTERMEASURES

There are several reliable, commercially available inertia switches which will shut off the vehicle's electrical system during a crash. These switches are omnidirectional, functioning during longitudinal and lateral impacts and rollovers. The use of an inertia switch to shut off all vehicle electrical power would eliminate all electrical ignition sources except sparks generated by metal coming in contact with the positive battery terminal. A plastic terminal shield can be designed and manufactured easily and cheaply to eliminate this ignition source.

7.5 COST/BENEFIT ANALYSIS

A combined ignition source and fuel spillage countermeasure system which would be 100 percent effective in eliminating crash fires would not be cost effective if the lower projected estimates of crash fires and burn fatalities are used in the analysis. If the higher projected estimates are used, the system would be marginally cost effective in ten years.

An electrical countermeasure system would become cost effective within three years following the introduction of the system into all new vehicles. Cumulative savings would exceed cumulative costs within five years. However, this system would not eliminate all crash fires and burn fatalities as the system is estimated to be only 85 percent effective in eliminating crash fires.

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APPENDIX

DEMONSTRATION CRASH TEST DATA PLOTS

This Appendix presents the remaining data plots for the demonstration crash tests discussed in Section 6.0. The accelerometer locations are illustrated in Figure 6-1 of this report.

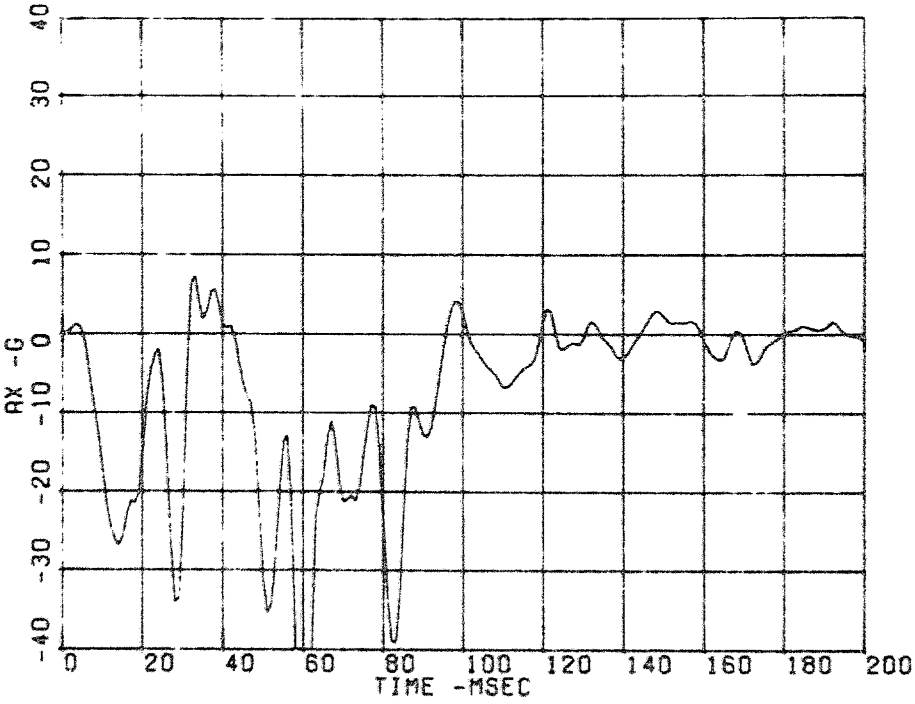

Figure A-1. Longitudinal Acceleration, Location 1 (Center Firewall), Barrier Test.

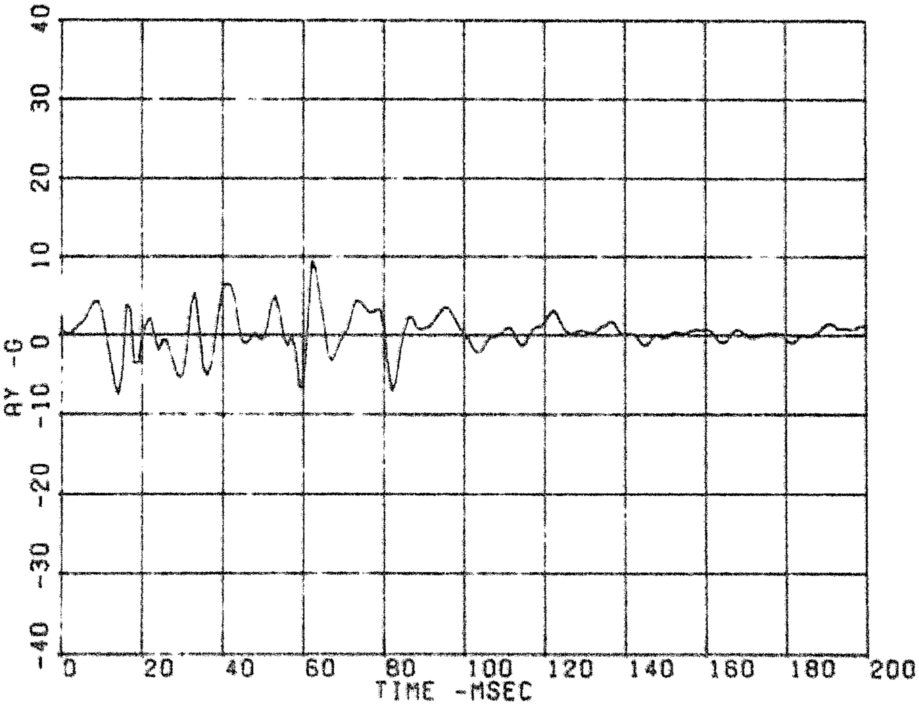

Figure A-2. Lateral Acceleration, Location 1 (Center Firewall), Barrier Test.

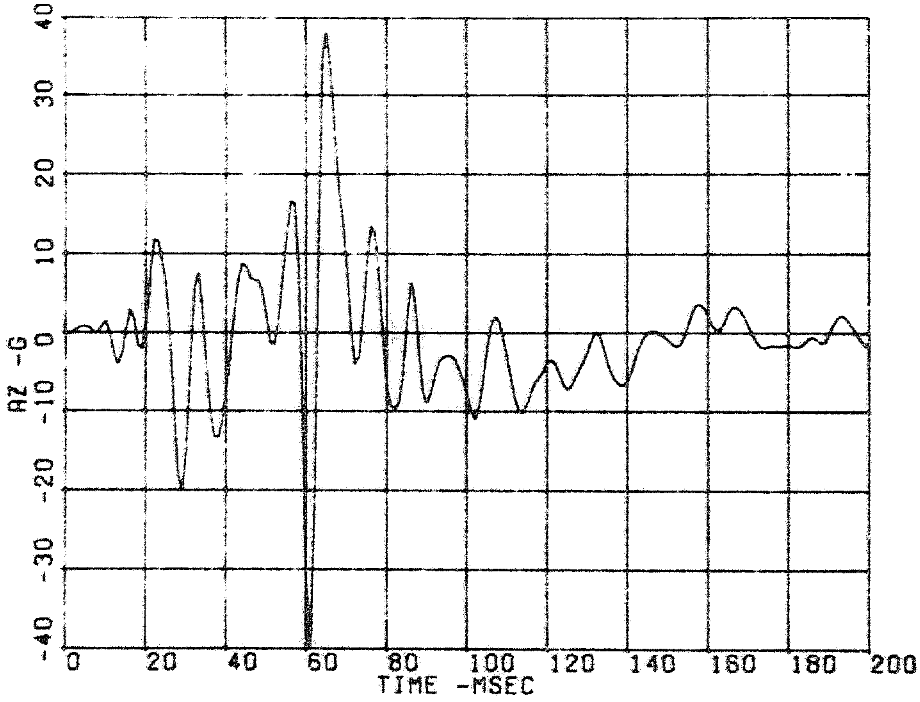

Figure A-3. Vertical Acceleration, Location 1 (Center Firewall), Barrier Test.

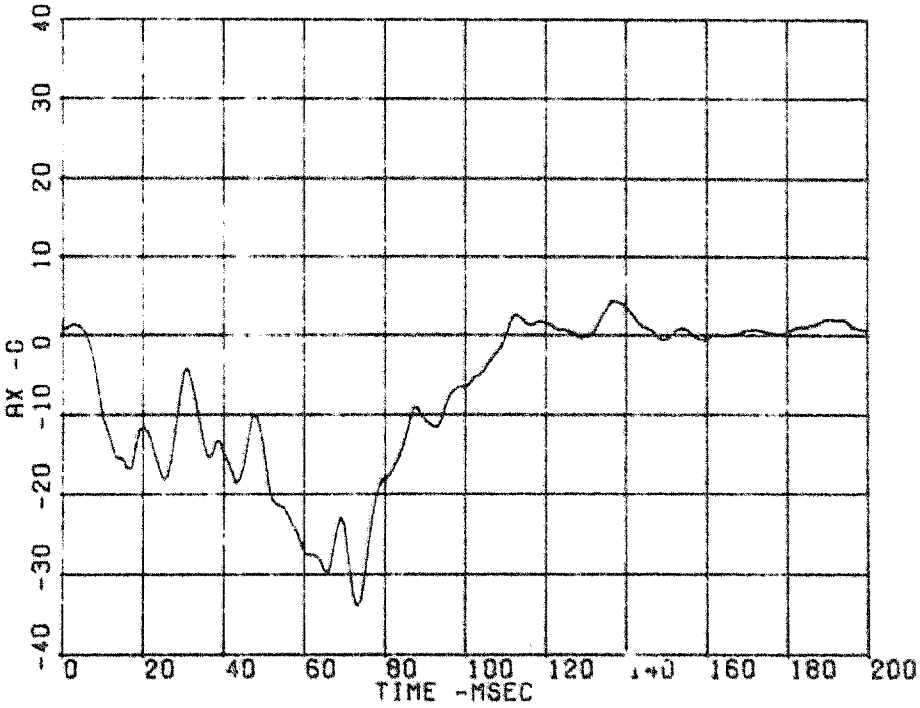

Figure A-4. Longitudinal Acceleration, Location 3 (Left Rear Frame) Barrier Test.

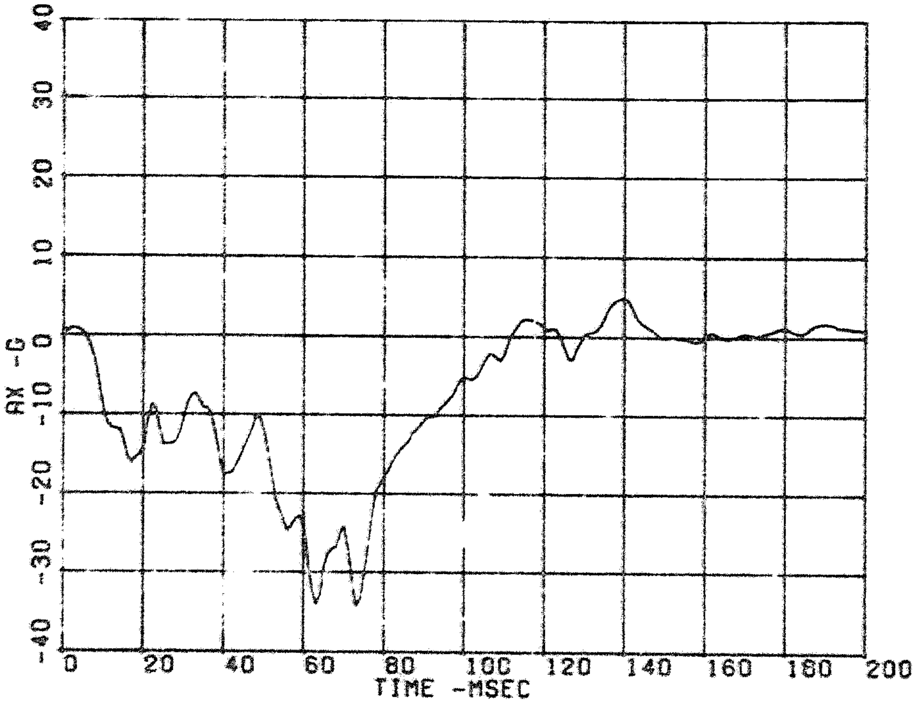

Figure A-5. Longitudinal Acceleration, Location 4 (Right Rear Frame), Barrier Test.

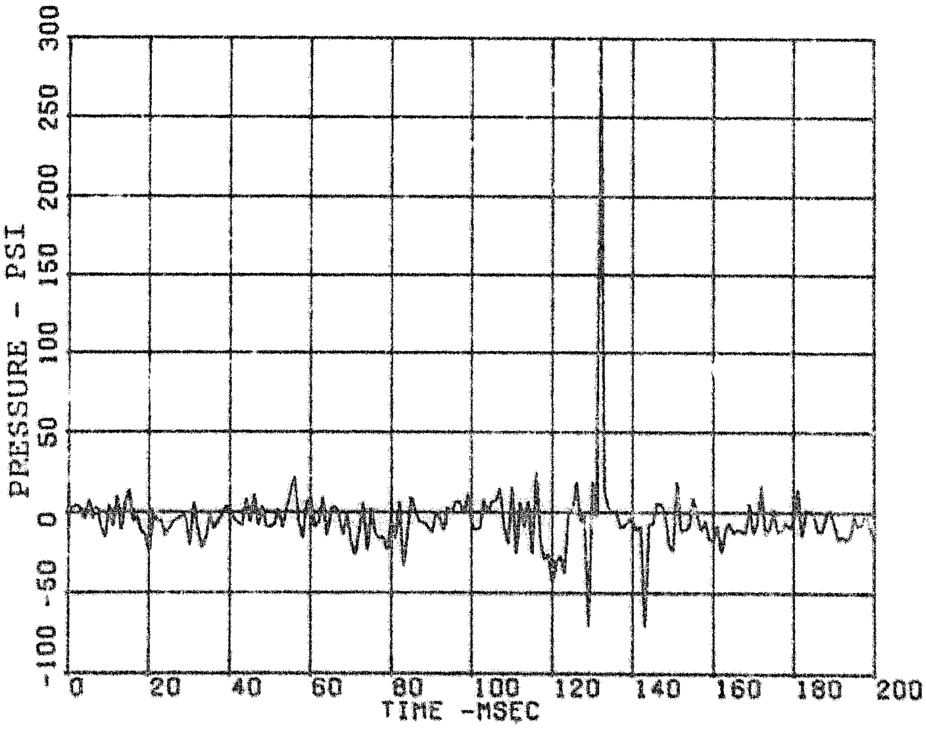

Figure A-6. Fuel Tank Pressure, Fuel System Countermeasures Front-to-Rear Test.

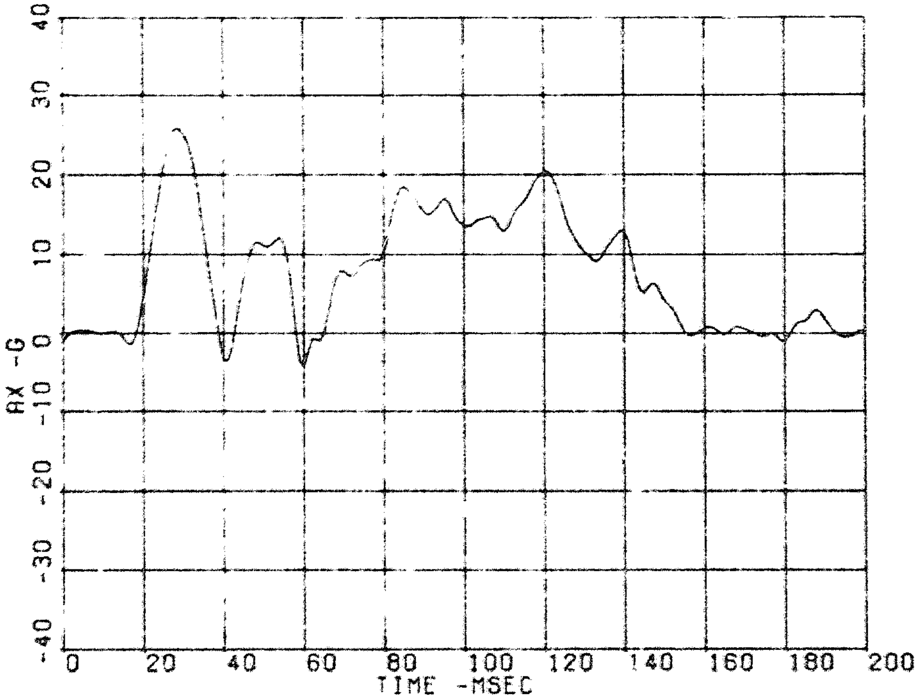

Figure A-7. Longitudinal Acceleration, Location 1 (Center Firewall), Fuel System Countermeasures Front-to-Rear Test.

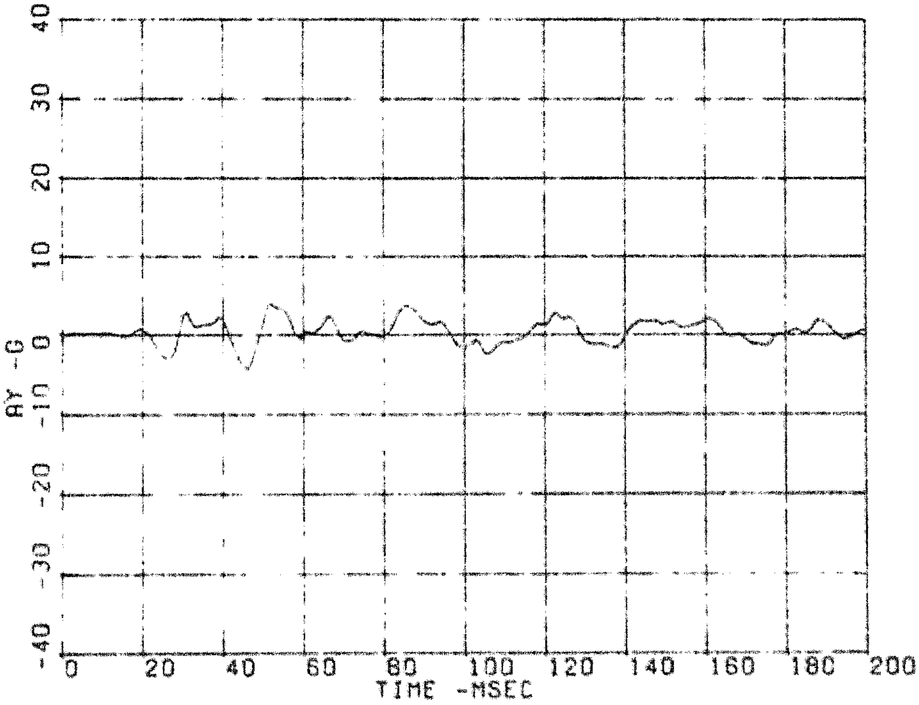

Figure A-8. Lateral Acceleration, Location 1 (Center Firewall), Fuel System Countermeasures Front-to-Rear Test.

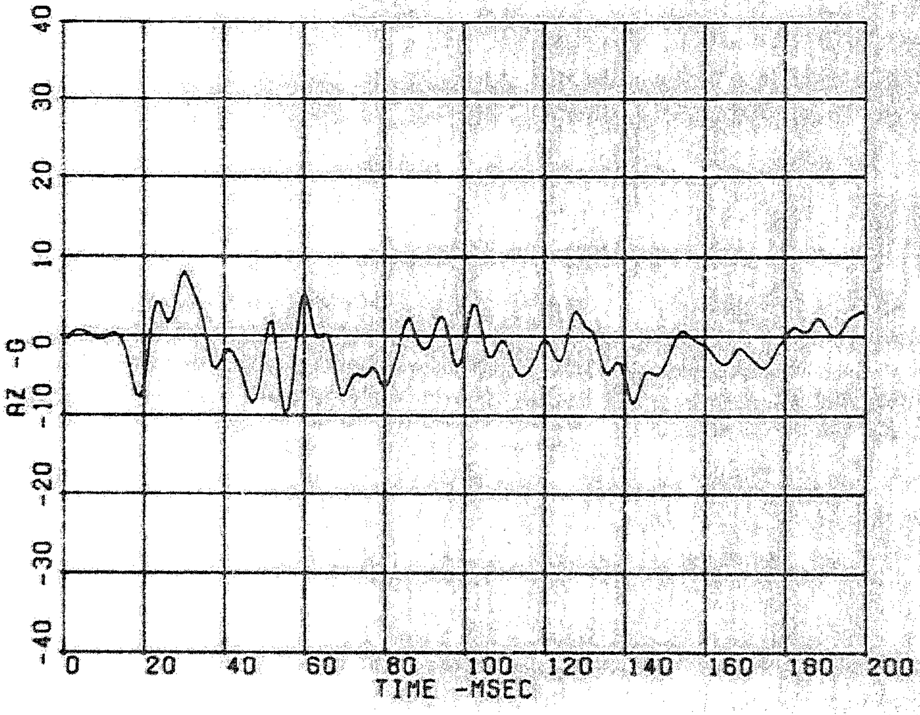

Figure A-9. Vertical Acceleration, Location 1 (Center Firewall), Fuel System Countermeasures Front-to-Rear Test.

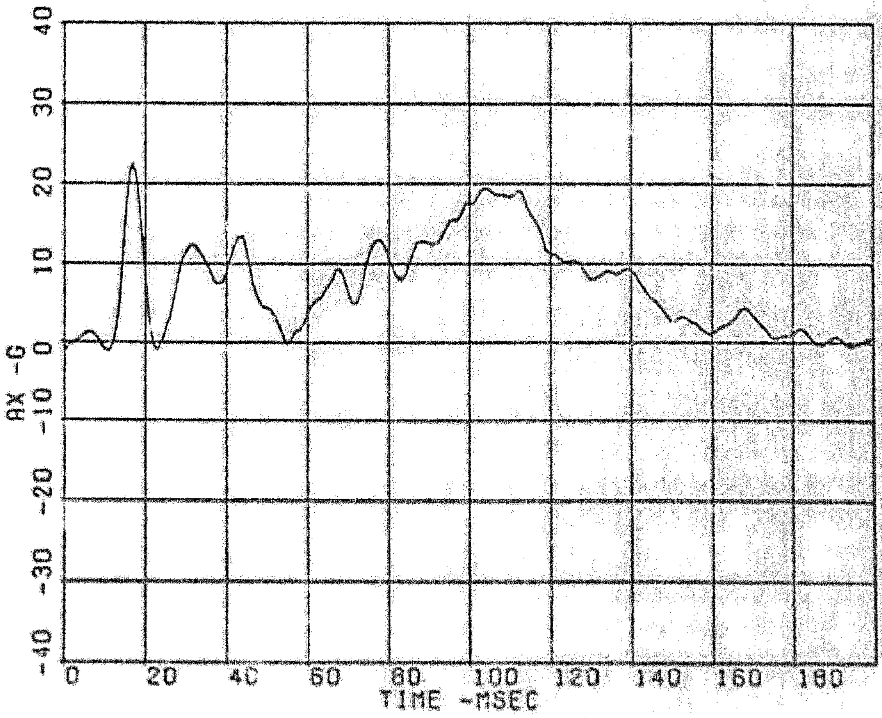

Figure A-10. Longitudinal Acceleration, Location 3 (Left Rear Frame), Fuel System Countermeasures Front-to-Rear Test.

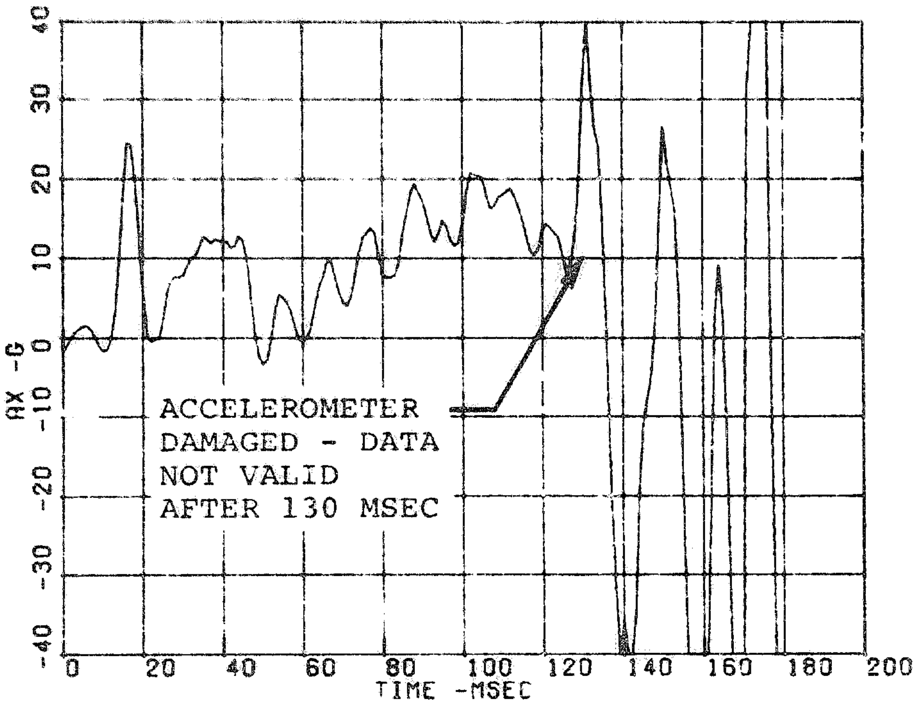

Figure A-11. Longitudinal Acceleration, Location 4 (Right Rear Frame), Fuel System Countermeasures Front-to-Rear Test.

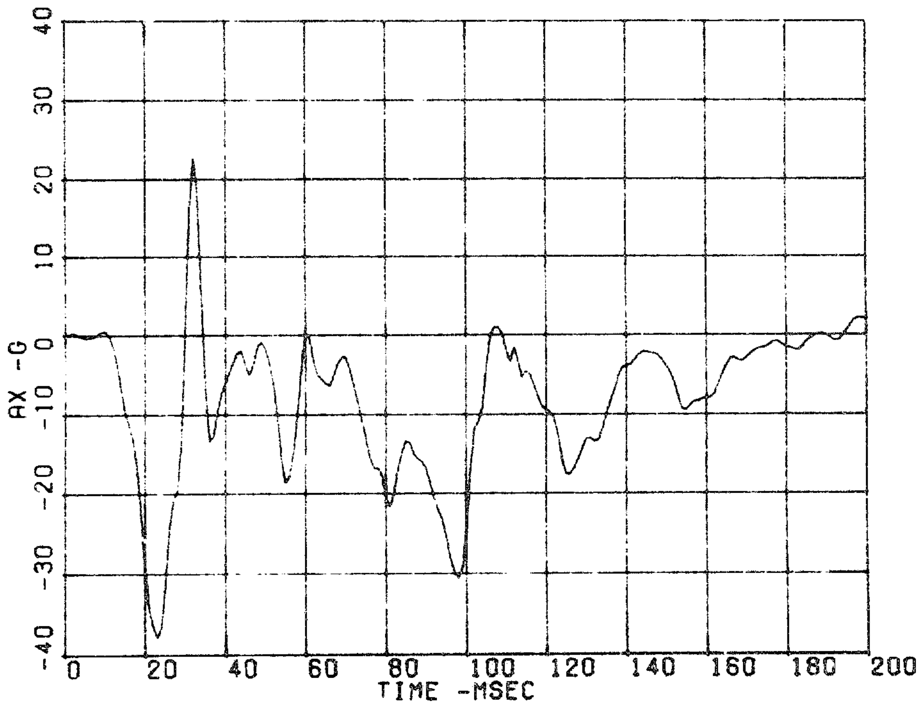

Figure A-12. Longitudinal Acceleration, Location 1 (Center Firewall), Ignition Source Countermeasures Front-to-Rear Test.

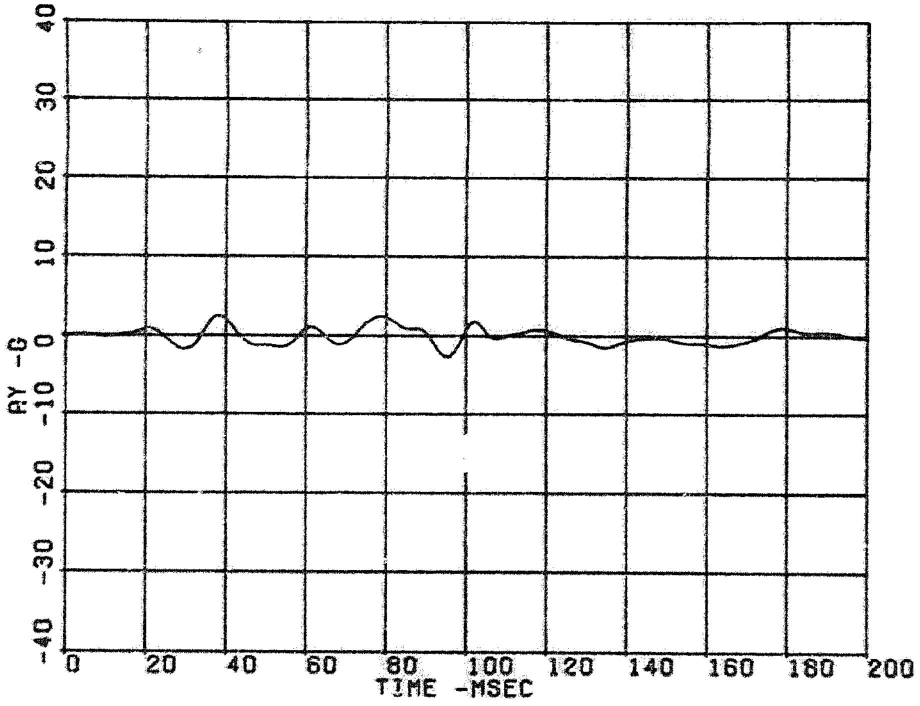

Figure A-13. Lateral Acceleration, Location 1 (Center Firewall), Ignition Source Countermeasures Front-to-Rear Test.

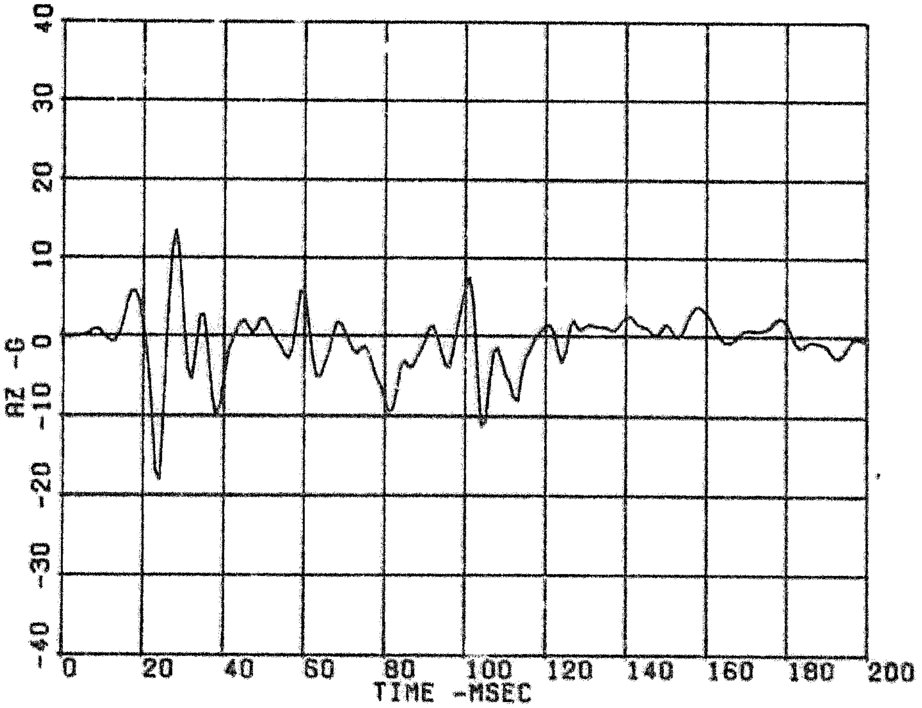

Figure A-14. Vertical Acceleration, Location 1 (Center Firewall), Ignition Source Countermeasures Front-to-Rear Test.

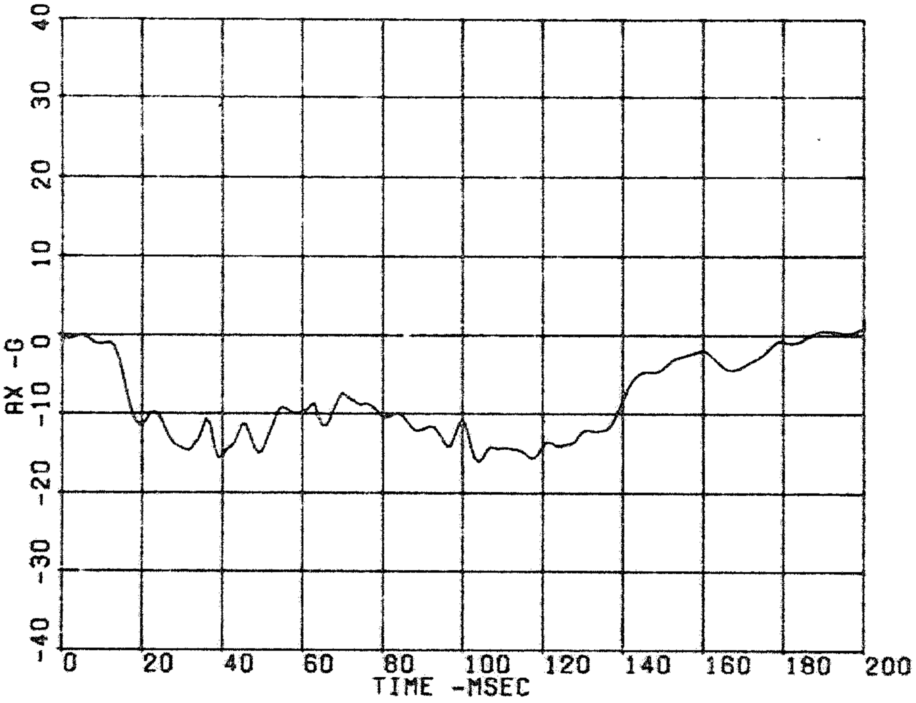

Figure A-15. Longitudinal Acceleration, Location 3 (Left Rear Frame), Ignition Source Countermeasures Front-to-Rear Test.

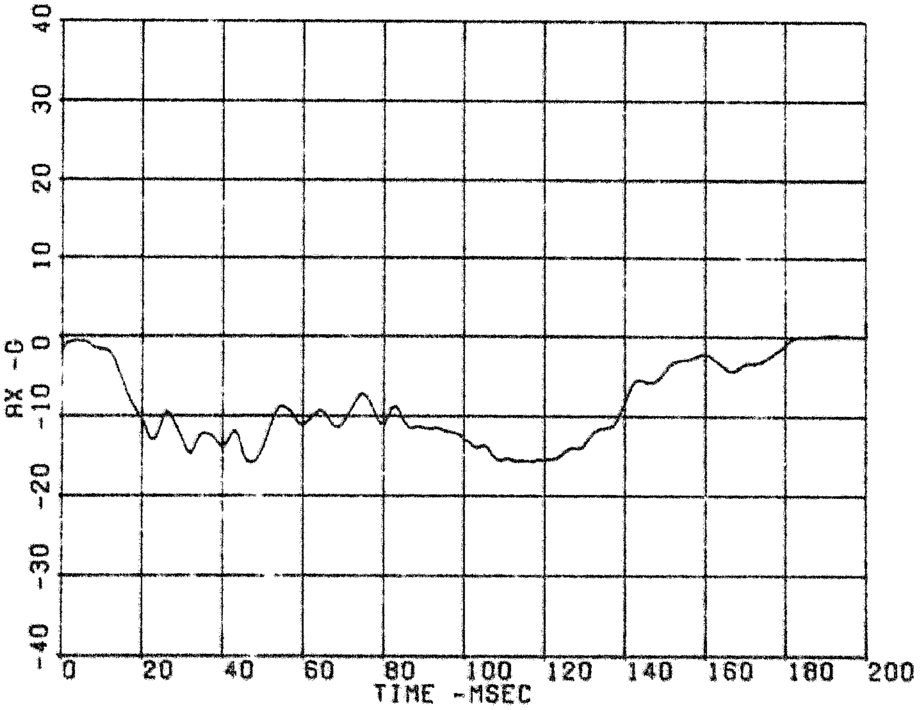

Figure A-16. Longitudinal Acceleration, Location 4 (Right Rear Frame), Ignition Source Countermeasures Front-to-Rear Test.

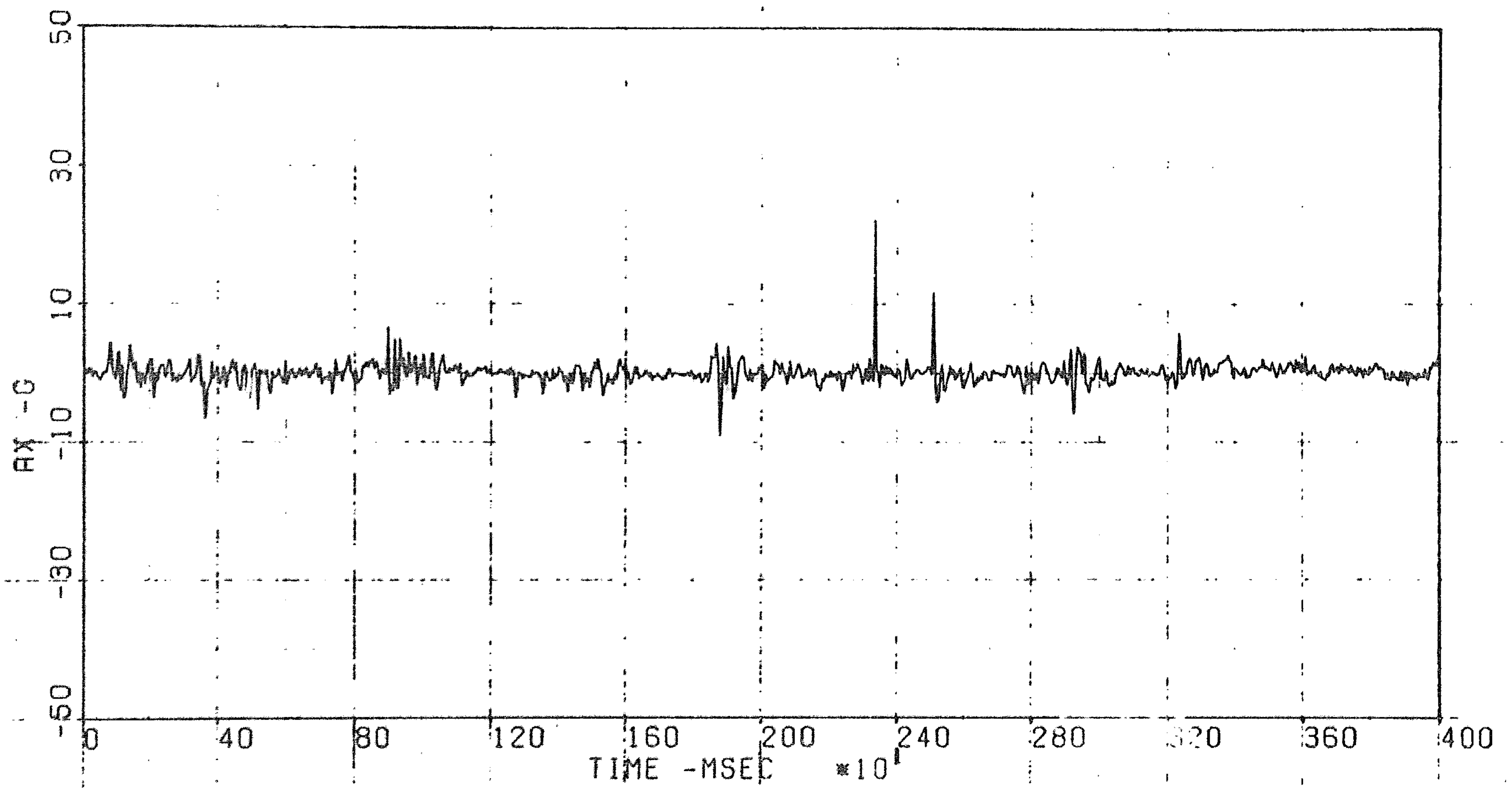

Figure A-17. Longitudinal Acceleration, Location 1 (Center Firewall), Rollover Test.

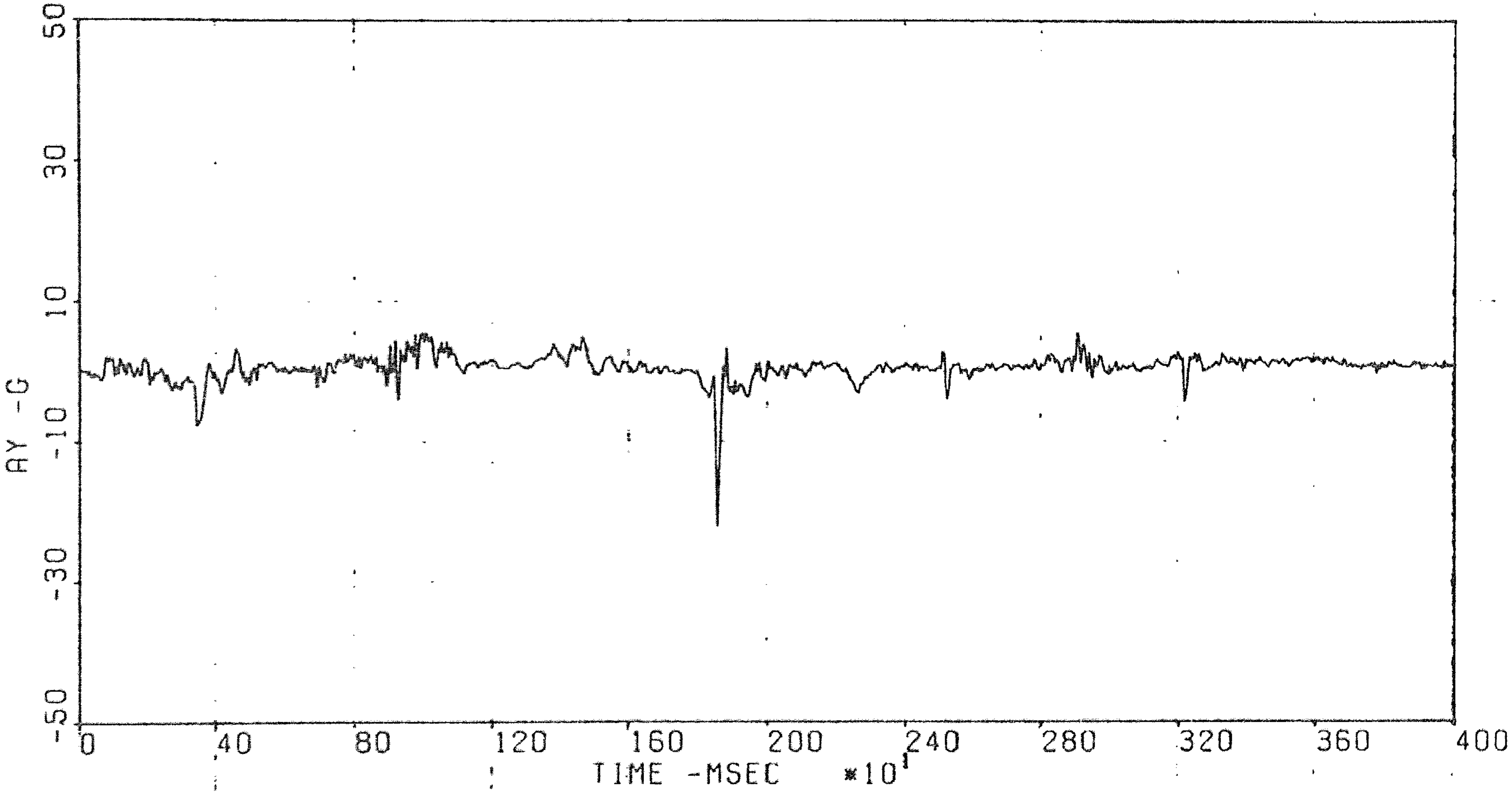

Figure A-18. Lateral Acceleration, Location 1 (Center Firewall), Rollover Test.

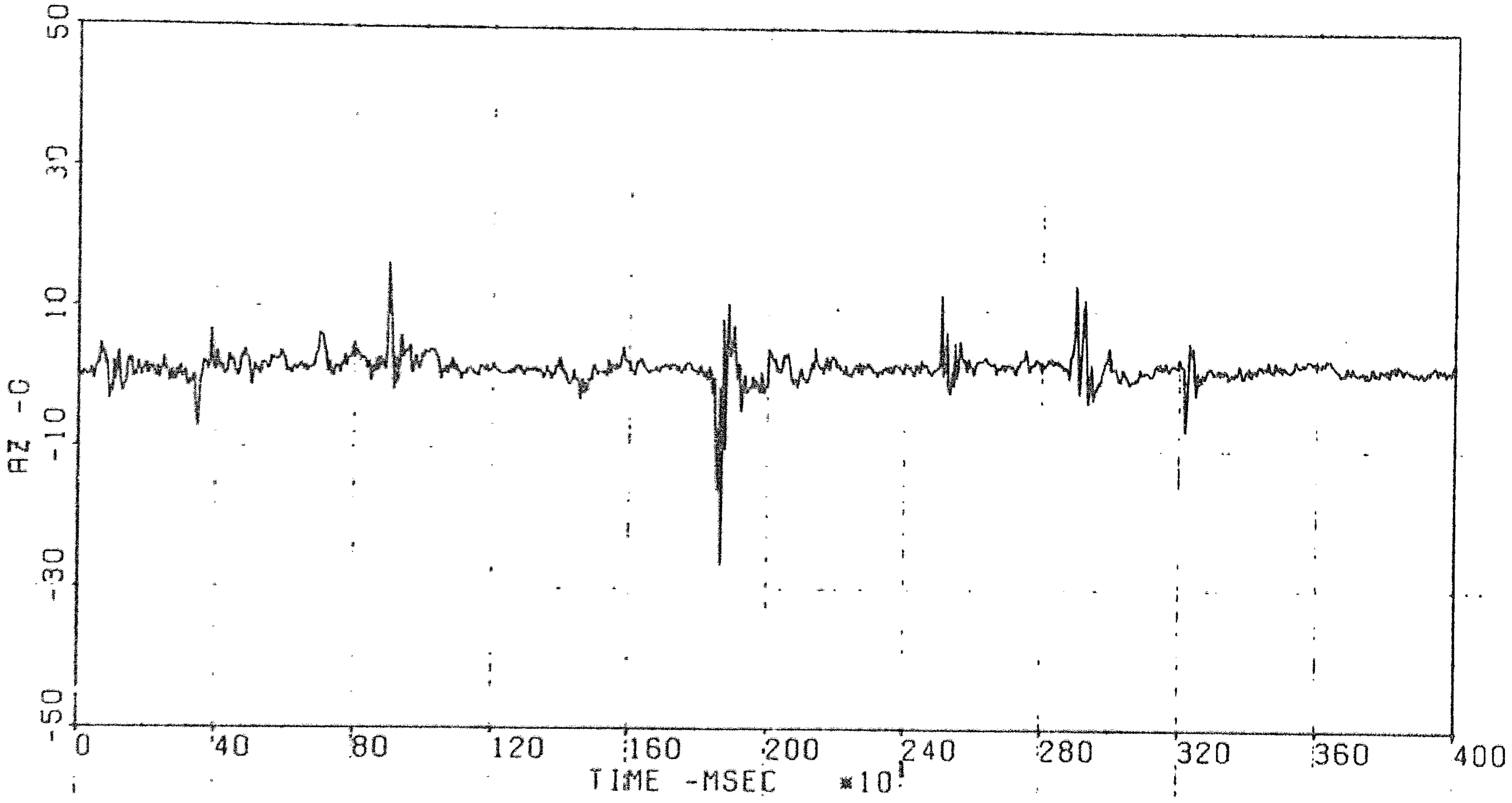

Figure A-19. Vertical Acceleration, Location 1 (Center Firewall), Rollover Test.

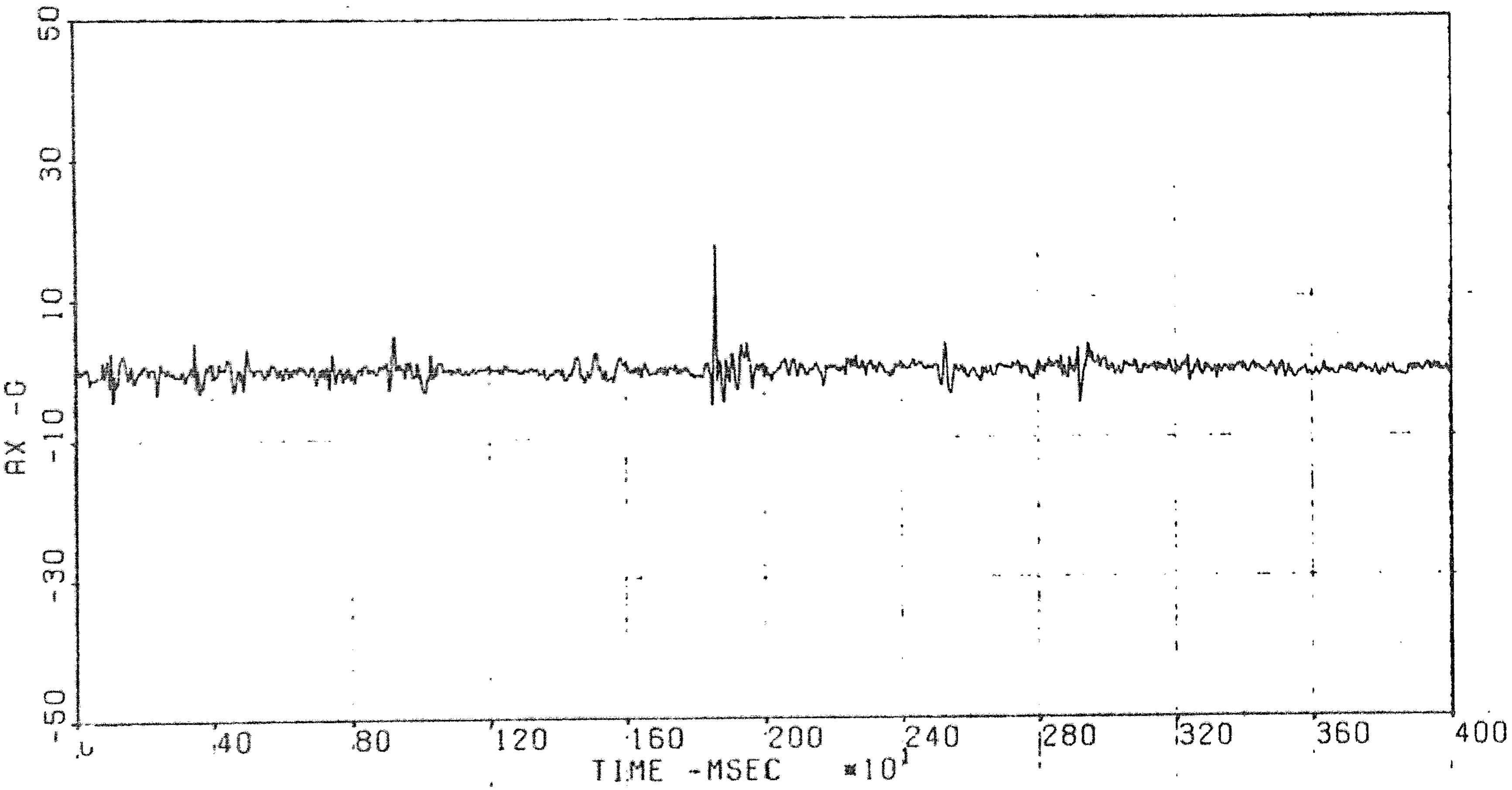

Figure A-20. Longitudinal Acceleration, Location 2 'Right Firewall), Rollover Test.

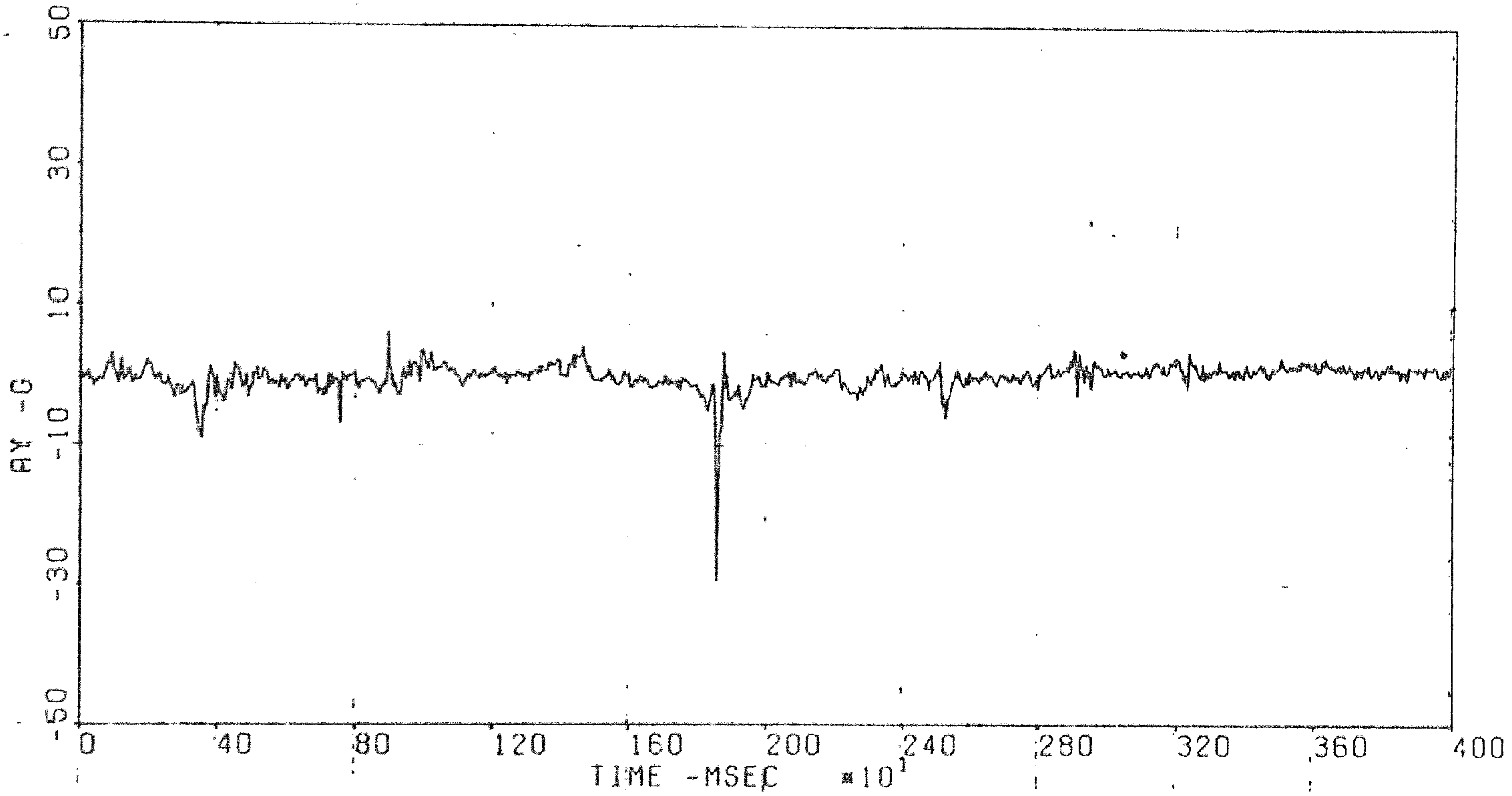

Figure A-21. Lateral Acceleration, Location 2 (Right Firewall), Rollover Test.

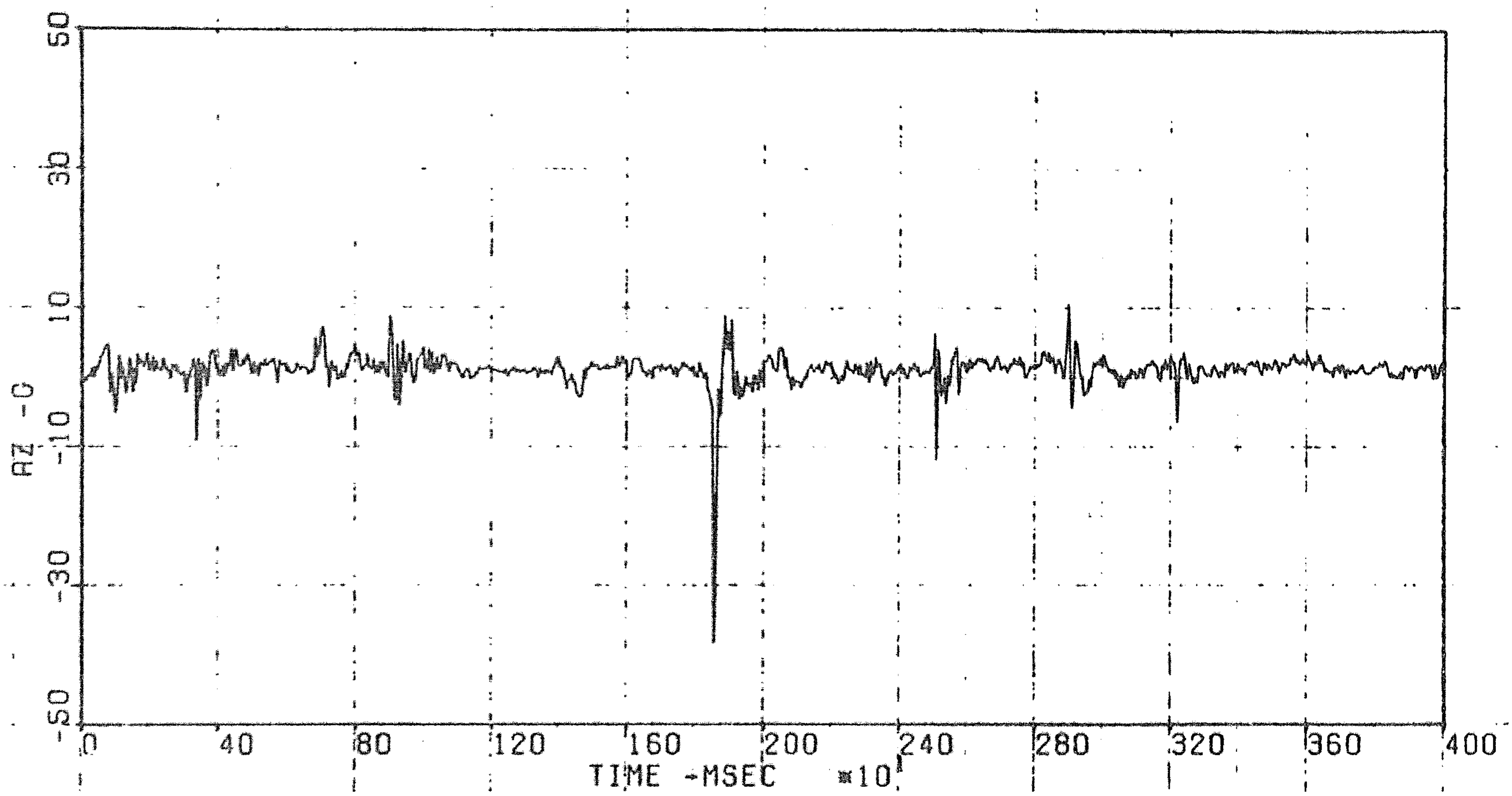

Figure A-22. Vertical Acceleration, Location 2 (Right Firewall), Rollover Test.