A RESEARCH PROGRAM TO STUDY IMPACT RELATED FIRE SAFETY

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ABSTRACT

The research reported in this paper is a follow-on to a five year research program conducted by General Motors in accordance with an administrative Settlement Agreement reached with the US Department of Transportation. In a subsequent Judicial Settlement, GM agreed fund more than $4.1 million in fire-related research over the period 2001-2004. The purpose of this paper is to provide a public update report on the projects that have been funded under this latter research program, along with results to date. This paper is the fourth in a series of technical papers intended to disseminate the results of the ongoing research.

The projects and research results to be reported in this paper include the following:

1. Comprehensive analyses and synthesis of data/research from studies sponsored by GM/DOT, MVFRI, and NHTSA
2. Statistical Analysis of Vehicle Fires
3. Analysis of data systems to assess possibilities for evaluating egress and fire penetration times, including times for first responder rescue and fire propagation.
4. An analysis of fire occurrence and rollover rates in national data systems.
5. Failure evaluation of a compressed hydrogen storage tank
6. 42-volt electrical system fire safety issues

The paper briefly summarizes the projects and reports the significant findings from each.

This paper documents six current research programs on fire safety technology. These programs involve analysis of field data, testing, and alternative fuel systems. This paper also provides a brief synthesis of data and research conducted under a previous GM/DOT research program.

INTRODUCTION

On March 7, 1995, the U.S. Department of Transportation (DOT) and General Motors Corporation (GM) entered into an administrative agreement, which settled an investigation that was being conducted by the National Highway Traffic Safety Administration (NHTSA) regarding an alleged defect related to fires in GM C/K pickup trucks [NHTSA 1994 and 2001].

Under the GM/DOT Settlement Agreement, GM agreed to provide support to NHTSA's effort to enhance the current Federal Motor Vehicle Safety Standard (FMVSS) No. 301, regarding fuel system integrity, through a public rulemaking process. GM also agreed to expend $51.355 million over a five-year period to support projects and activities that would further vehicle and highway safety. Ten million dollars of the funding was devoted to fire safety research [NHTSA 2001]. This project is referred to as the GM/DOT Settlement research program.

Subsequent to the GM/DOT Settlement, GM agreed to fund an additional $4.1 million in research related to impact induced fires. This latter research project was included under the terms of a judicial settlement. The fuel safety project objectives are defined by the White, Monson and Cashiola vs. General Motors Agreement dated June 27, 1996 [Judicial District Court, 1996]. All research under the project will be made public for use by the safety community. The purpose of this paper is to provide a public report on the projects that have been recently funded under this research program, along with results to date.

ANALYSIS AND SYNTHESIS OF FIRE RESEARCH

The GM/DOT Settlement research program in motor vehicle fire safety has been analyzed and synthesized by a team of fire experts led by FM Global. Of particular interest has been the analysis of eleven crashed vehicle burn tests. These tests subjected crashed vehicles to under-hood and spilled fuel fires of an intensity that could be possible after a crash. Eight of the tests explored the fire growth and spread under a variety of baseline conditions. Three tests were primarily for the purpose of evaluating countermeasures to increase the time for fire to penetrate the occupant compartment. Among the baseline tests there were three vehicles that had been subjected to rear crash tests. One was a passenger car, one was a minivan, and the other an SUV. These vehicles were subjected to pool fires under the rear of the vehicle. The other four baseline tests were vehicles that had been subjected to frontal crash tests. One of these was a passenger car subjected to a pool fire under the vehicle in the rear. The others were subjected to under-hood fires with ignition sources either at the battery location or by the ignition of sprays and pools of mixtures of hot engine compartment fluids from a propane flame located in and below the engine compartment.

Three additional tests were conducted to evaluate countermeasures. The effectiveness of a fire retardant treatment of the HVAC unit was evaluated by tests of engine compartment fires in 2 vehicles with frontal damage. One of the vehicles was tested with the treatment and the other without. The other countermeasure was an intumescent coating on the underbody of the vehicle. The SUV pool fire baseline test was replicated to evaluate this countermeasure.

A list of the tests and vehicles is as follows:

1. 1996 Dodge Caravan-front crash and fire started in the engine compartment;
2. 1996 Plymouth Voyager-rear crash and fire started by igniting the gasoline pool under the vehicle;
3. 1997Chevrolet Camaro-rear crash and fire started by igniting gasoline pool under the vehicle;
4. 1997Chevrolet Camaro-front crash and fire started in the engine compartment;
5. 1997 Ford Explorer-rear crash and fire started by igniting gasoline pool under the vehicle;
6. 1997 Ford Explorer- front crash and fire started by igniting gasoline pool under the vehicle;
7. 1998 Honda Accord-rear crash and fire started by igniting gasoline pool under the vehicle;
8. 1998 Honda Accord-front crash and fire started in the engine compartment;
9. 1999 Chevrolet Camaro- FR HVAC- front crash and fire started in the engine compartment;
10. 1999 Chevrolet Camaro-non-FR HVAC control-front crash and fire started in the engine compartment;
11. 1999 Ford Explorer undercarriage coated with intumescent paint–rear crash and fire started by igniting gasoline pool under the vehicle.

An in-depth analysis of these tests has been published [Tewarson, 2005; Tewarson 2005]. The objectives of the analysis were to investigate the ignition and flame spread behaviors of engine compartment fluids and polymer parts, to assess time to flame penetration into the passenger compartment and to assess the creation of untenable conditions in the passenger compartment.

The analysis found significant differences between the flame penetration times into the passenger compartment in the front and rear crashed vehicle tests. In the rear crashed vehicle burn tests with ignition of gasoline pools under the vehicle, flame penetration time into the passenger compartment varied between 0.5 to 3.0 minutes. For the front crashed vehicle burn tests with ignition in and under the engine compartment, flame penetration time into the passenger compartment varied between 10 to 24 minutes.

Once the flame penetrates the passenger compartment, the environment rapidly becomes untenable. In some burns, the passenger compartment became untenable before flame penetration. The untenable conditions were due to heat exposure (burns) and exposure to fire products (toxicity and lethality). The time between flame penetration and untenability of the passenger compartment varied from minus 2.5 to plus 3.2 minutes.

In general, polymeric parts in the engine and passenger compartments burn as molten pool fires with high release rates of heat, CO, smoke, and other toxic compounds, typical of ordinary polymers. Pool fires of the molten polymers are the major contributors to the vehicle burning intensity and contribute towards the penetration of flames into the passenger compartment. The fire retardant treatments of the polymer parts that were tested in the program proved ineffective in delaying fire penetration into the passenger compartment.

Additional testing has been conducted by Biokinetics and Associates, Ltd. to evaluate under-hood temperatures of different classes of vehicles [Fournier, 2004]. The results showed considerable difference between the maximum temperatures of different vehicles when operated under load. In a standardized uphill test, the maximum temperature measured on the exhaust manifold varied from a low of 241 ^{o}C for a minivan to a high of 550 ^{o}C for a passenger car.

STATISTICAL ANALYSIS OF VEHICLE FIRES

An earlier paper reported on an analysis of data from the Fatal Accident Reporting System (FARS) to determine fire frequency in fatal crashes (Digges 2003, Friedman 2003, Friedman 2005). The study examined fires in vehicles 1-4 years old. The analysis indicated that fatality rates by most harmful event have declined by 72.3% for cars and 79.7% for LTVs between the late 1970's and the early 1990's. Since 1990, the fire rate for all classes of vehicles has remained fairly constant. In 2000, the fire rate in fatal crashes was 5.14 fires/MVY for passenger cars and 6.39 fires/MVY for light trucks.

More recent FARS analysis [Fell, 2004, Bahouth 2005] has focused on identifying the crash modes that are most frequently involved in fires. Data for the combined years 1994 to 2003 were examined. For those years, the average annual number of fatal crashes with fire involvement was 1,596. Fire was the most harmful event for an average of 432 fatally injured occupants each year. Among these fatally injured occupants approximately 23% were also coded as being entrapped.

FARS does not record crash direction. However, the location of principal damage is coded. In this coding, rollovers with damage from impacts with fixed objects or with other vehicles are coded according to the location of the damage. If the damage comes from ground contact, the crash is classified as a non-collision. Consequently, most rollovers are classified as non-collision. For the fatal population with fire as the most harmful event, the distribution by damage areas is shown in Figure 1.

Figure 1 also shows the distribution of vehicle damage for crashes with both fire and entrapment where fire was the most harmful event. Note that only 23% of the crashes with fire as most harmful event also had entrapment. For the crashes with both fire and entrapment, 98.8% were coded as also having disabling deformation. Disabling deformation is the most severe of the three deformation categories available in FARS.

Most harmful event applies to the vehicle - not the persons in the vehicle. Therefore, one can not assume that the most harmful event for a vehicle was the cause of any death or injury for any specific individual within the vehicle.

Figure 1 shows that over 60% of the fires and entrapments with fires occur with frontal damage. There is not much difference between the frequency of fire between the left and right side damage. Rear damage appears to have the highest entrapment rate.

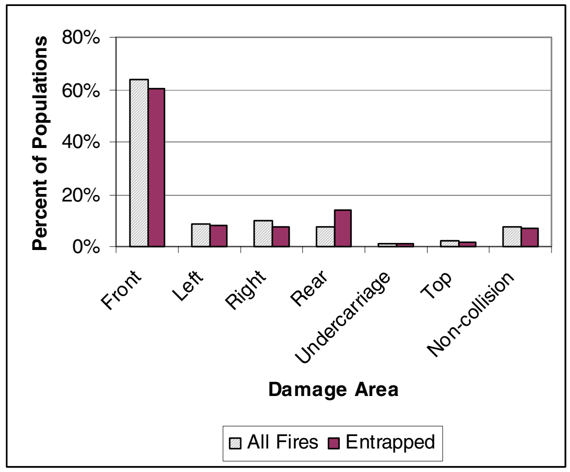

Figure 1. Percentages of Crashes with Fire as the Most Harmful Event and Percentages of Crashes with both Fire as the Most Harmful Event and Entrapment by Vehicle Damage Area

To gain further insight into crashes with fires, the NASS/CDS (National Automotive Sampling System / Crashworthiness Data System) was examined [Bahouth 2005]. This project analyzed 531 crashes in which there was an occurrence of fire. This represented 78,000 (weighted) vehicle fire occurrences over an eight year period from 1994 through 2002. Of these cases, about 49% of the fires were minor and 51% major, based on weighted data. A "major" fire is classified a fire with external origin that spreads into the passenger compartment or a fire that originates inside the passenger compartment and spreads. A "minor" fire is defined as one that does not spread in or into the passenger compartment.

The above population of crashes had 830 occupants with 350 MAIS 3+ (serious) injuries, including 188 fatalities. These unweighted numbers were expanded to 105,962 occupants with 20,000 MAIS 3+ injuries and 10,348 fatalities. When fire was the most harmful event, the corresponding numbers of MAIS 3+ injuries and fatalities were 100 and 83, respectively. These numbers expanded to 5,766 MAIS 3+ and 4,744 fatalities. This averages 527 fatalities per year – which is in approximate agreement with the 432 fatalities peer year identified in FARS.

The influence of crash mode (crash direction) on fire severity and fire origin are shown in Figure 2. The percentages in this figure add to 100 per cent and represent the exposed occupants rather than the population of vehicles. Rollovers are defined as any crash with at least one quarter-turn of roll. About half of the occupants in rollovers with fires were exposed to a planar crash prior to the rollover. The most frequent planar crash mode that preceded a rollover was a side impact. A side impact followed by a rollover accounted for 19% of the minor fire category and 10% of the major fire category. A frontal crash followed by a rollover accounted 2% and 14%, respectively.

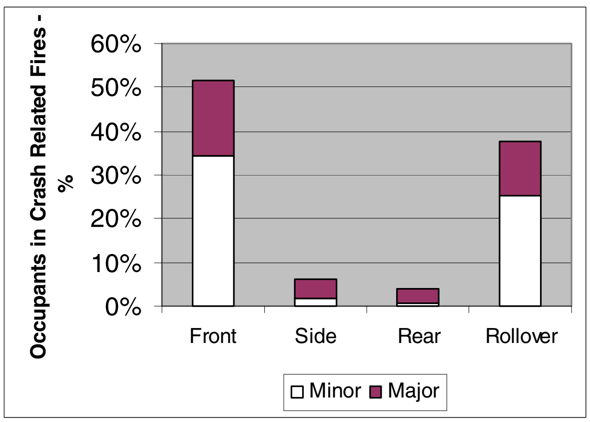

Figure 2. Occupants in Crash Related Fires by Crash Mode and Fire Severity from NASS/CDS 1994-2002.

The location of major and minor fires is shown in Table 1. Two categories, under hood and fuel tank, comprise 92.5% of the major fires. These two categories are examined in more detail in the tables to follow. Table 2 is a breakout of minor and major fuel tank fires by crash direction. Table 3 gives a similar breakout for engine compartment fires.

Table 1.
Location of Major and Minor Fires in NASS/CDS 1994-2002 Based on Weighted and Unweighted Data

Fire Location	Weighted	Unweighted
Minor Fire		
Fuel Tank	1.3%	3.3%
Under Hood	85.4%	86.2%
Dashboard	8.5%	2.1%
Other	4.8%	8.4%
Major Fire		
Fuel Tank	22.5%	25.5%
Under Hood	70.0%	64.4%
Dashboard	0.8%	2.2%
Other	6.6%	7.9%

Table 2 shows the percent of occupants exposed to minor and major fires that have the fuel tank coded as the origin. The numbers were extracted from NASS/CDS 1994-2002. The percentages were based on weighted data and add to 23.8%, the percentage of under hood fires shown for the weighted data in Figure 1.

In Tables 3 and 3, any vehicle that rolled one quarter-turn or more was considered a rollover, even if it had a previous impact. Nineteen percent of the major fires had rollovers plus a planar crash. The most common, a frontal crash followed by a rollover, comprised 13% of the major fire crashes. A side crash followed by a rollover comprised 9.3% of the minor fire cases.

Table 2.
Crash Modes for Occupants Exposed to Minor and Major Fuel Tank Fires from NASS/CDS 1994-2002

Crash Mode	Minor	Major	Total
Frontal	0.8%	0.6%	2.1%
Nearside	0.0%	3.1%	2.9%
Farside	0.0%	2.6%	2.5%
Rear	0.3%	4.9%	5.2%
Rollover	0.2%	11.4%	11.2%
All	1.3%	22.5%	23.8%
Number	1163	10307	11470

Table 3.
Crash Modes for Occupants Exposed to Minor and Major Under Hood Fires from NASS/CDS 1994-2002

Crash Mode	Minor	Major	Total
Frontal	41.7%	51.9%	44.7%
Nearside	0.9%	2.8%	1.4%
Farside	0.4%	2.9%	1.1%
Rear	0.0%	2.0%	0.5%
Rollover	26.9%	25.8%	26.9%
All	70.0%	85.4%	74.6%
Number	54,445	23,201	77,646

Table 2 shows that about 24% of the fires are associated with the fuel tank, and the vast majority of them are major fires. Rollovers are now the most frequent crash mode when the fuel tank is the source of the fire. Side impacts are second.

Table 3 shows that about 75% of vehicle fires in NASS/CDS are reported as engine compartment fires, when both major and minor fires are included. For major fires, the figure is 70%. Over 80% of these engine compartment fires were subsequent to a frontal collision or a frontal collision followed by a rollover.. This is consistent with the FARS data from Figure 1 that shows over 60% of the cases with fire as the most harmful event have frontal damage.

The vast majority of the crashes in NASS/CDS with engine compartment fire did not report any fuel leaks. However, about 7% of the fires were associated with the lines/pumps. There is no coding available for a flammable substance leakage within the vehicle other than a fuel system leakage. Consequently, there may be power steering fluid, brake fluid, coolant, window washer fluid leakage, or oil pan leakage, which was responsible for feeding the fire but was not reported. As noted, the majority of these engine compartment fires are reported as major fires. This may suggest that these engine fires are fed by the flammable substances found within the engine compartment.

In the majority of engine compartment fires, there was no entrapment reported. The distribution of entrapment for engine compartment fires is shown in Table 4. Of all crashes with engine compartment fires, 6.1 % had entrapment. Where there was entrapment in vehicles with engine compartment fires, most fires were major and almost 40% of the injured occupants were categorized with MAIS 6 (fatal) injuries. In about 90% of the MAIS 6 injured occupants in engine compartment fire crashes, there was entrapment. Where entrapment and an engine compartment fire were reported, 66% of the injuries were MAIS 3+.

Table 4 indicates that the most frequent classification of occupant entrapment is associated with mechanical entrapment of the occupant inside the vehicle.
In general (not just those with fires in the engine compartment), entrapment was reported in 6.6% of all fire crashes. 58% of fire with entrapment cases are MAIS 3+ injuries. MAIS 6 injuries are coincident with about 92% of the fire crashes reporting entrapment.

Table 4.
Entrapment Occurrences and Fire Severity for Under Hood Major and Minor Fires from NASS/CDS 1997-2002.

Entrapment Type	Major	Minor
Not Entrapped	67.6%	26.3%
Occupant Entrapped	4.2%	0.6%
Vehicle Jammed	0.8%	0.5%
Total	72.6%	27.4%

RESCUE TIMES

A study was undertaken by Dr. George Bahouth to provide real world data to characterize crash involved populations, rescue timing, and crash characteristics for occupants to evaluate the benefit of increased fire protection following a crash event. The study utilized a variety of data sources [Bahouth, 2004].

A major fire is defined in NASS/CDS as one that spreads from outside the vehicle to the occupant compartment, or if it originates in the occupant compartment spreads beyond its area of origin. There is little information in NASS about how rapidly the minor fires spread to become major fires. However, delaying the fire spread might be beneficial, particularly to any occupants who are disabled, who are seriously injured by the crash forces, or who are entrapped inside the vehicle.

The analysis of rescue times sheds light on the value of countermeasures to increase the vehicle's resistance to fire penetration of the occupant compartment.

The National Fire Incident Reporting System (NFIRS) was used to establish the distribution of rescue times for both rural and urban areas. The information for each NFIRS case is reported by fire and rescue personnel from a subset of all fire stations around the country. Following case collection, each event type within NFIRS is assigned a weighting ratio which inflates case counts to national estimates. These inflation or weighting factors are based on case counts from the National Fire Protection Association (NFPA) annual survey. Approximately 1/3 of all fire stations contribute case information to the NFIRS database. Because NFIRS is a registry of all types of fire related events (i.e. building fires, forest fires and motor vehicle fires) only a subset of reported cases are motor vehicle related. NFIRS records the time between receipt of the call and arrival on scene.

The FARS data also records the rescue time when it is available. In FARS, two times are recorded. The first is the time between the notification of rescue and the arrival on scene. The second is the time between the crash and the arrival of rescue on the scene.

Table 5 shows the distribution of response times by land usage, based on NFIRS and FARS data. The NFIRS times shown are the period from receipt of the call to arrival on scene. Additional time delay may exist between the crash and the call to 911. The FARS data shows both the call to rescue time and the crash to rescue time. Additional time beyond that shown may be required to manage the fire and extract the occupants.

Table 5.
Response Time Percentiles in Minutes by Land Use Based on NFIRS and FARS Records

		Percentiles in minutes	
Data Source	**Time Period**	**50%**	**75%**
NFIRS URBAN	Call to Rescue	5	8
NFIRS RURAL	Call to Rescue	7	10
FARS URBAN	Call to Rescue	5	8
FARS RURAL	Call to Rescue	9	14
FARS URBAN	Crash to Rescue	8	12
FARS RURAL	Crash to Rescue	15	24

Using NASS/CDS, the distribution of extrications (occupant entrapment) was investigated versus crash severity. For frontal crashes, nearly 50% of the entrapments occurred during crashes with a deltaV of 17 mph or less. By crash direction, the delta-v for 50% entrapment were: 16 mph for nearside crashes; 20 mph for farside crashes; and 16 mph for rear impacts.

FIRES IN ROLLOVER CRASHES

Rollovers are increasing in numbers in the overall accident statistics. Previous studies of state data have indicated that rollovers may carry an increased risk of fires [Friedman, 2003, Friedman 2005, and Digges, 2004]. An examination of FARS further supports this finding [Fell, 2004]. For FARS, the risk of a fire in any fatal crash was 2.18%. The risk of a fire in a fatal rollover crash was 3.89%, an increased risk of 78%. The percent of fatal crashes with rollovers was 17.9%. The percent of fatal crashes with fires that were rollovers was 24.9%. There are an average of 420 vehicles per year in fatal crashes with fire and rollover.

Crashes that involved rollover and a fire occurrence were further investigated using 1997-2002 NASS/CDS [Bahouth, 2005]. There were 72 cases in the database with rollovers and fires. The reported data are unweighted due to the limited number of available cases. Table 6 shows that the majority (67%) of the fires occurred in the engine compartment subsequent to a rollover. Of these, 42% were major fires in severity. When the fire occurance was caded as the fuel tank/filler neck (19% of the total), 71% of the resulting fires were major.

Table 6.
Fire Occurrences in Rollover Crashes from NASS/CDS 1997-2002.

Fire Location	Minor	Major	Total
Under Hood	39%	28%	67%
Fuel Tank/Filler	5.6%	14%	19%
Instr. Panel	0.0%	2.8%	2.8%
Exh. System	1.4%	0.0%	1.4%
Other/Unknown	6.9%	2.8%	10%
Total	53%	47%	100%

Due to the high percentage of engine compartment fires, these were examined in more detail. The leakage locations are shown versus fire severity in Table 7. This table includes only the 48 cases where the fire was in the engine compartment after a rollover occurred. No fuel leakage source was identified in most of the fires. There is, moreover, no coding in NASS/CDS for leakage of other flammable fluids. Consequently, the extent to which other engine compartment fluids or polymers may have contributed to the fire can not be determined.

Table 7.
Distribution of Leakage Location for Engine Compartment Major and Minor Fire Occurrence in Rollover Crashes

Leakage Location	Major	Minor	All
Cap/Filler Tube	2	1	3
Fuel Lines	1	0	1
Tank	1	0	1
No Fuel Leak	11	25	36
Other	1	0	1
Unknown	4	2	6

RESEARCH IN FIRE SAFETY FOR HYDROGEN-FUELED VEHICLES

Research to explore fire safety issues that may be associated with hydrogen fueled vehicles has been undertaken. The initial project was to explore fire safety issues with on-board hydrogen storage tanks.

The existing and proposed standards for compressed natural gas containers were used as guides.

Federal Motor Vehicle Safety Standard (FMVSS) No. 304, *Compressed natural gas fuel container integrity* requires a bonfire test. Draft International Standard ISO 15869-1, *Gaseous hydrogen and hydrogen blends – Land vehicule fuel tanks – Part 1: General requirements* also contemplates a bonfire test. Both procedures expose a compressed hydrogen cylinder at its working pressure to a 65-in. (165-cm) long bonfire.

Tests are performed with the tank manufacturers' specified fire protection system in place (e.g., pressure relief devices). FMVSS 304 requires a cylinder to either not rupture during a 20-min bonfire test, or to safely vent its contents through a pressure relief device. ISO 15869-1 requires a hydrogen cylinder to vent its contents prior to rupture.

The high pressures required for compressed hydrogen storage has resulted in the extensive use of composite tanks. These materials have lower thermal conductivity and fire resistance than the metal and metal lined tanks conventionally used at lower pressures for natural gas storage.

A research bonfire test of a 5000 psi hydrogen fuel tank was conducted by SwRI. [Weyandt, 2005, Zalosh 2005]. The objective was to test the tank to failure and study the properties of the tank and its contents prior to failure. In addition, the magnitude and characteristics of the energy release at failure were determined. Safety measures typically required on compressed gas cylinders (pressure relief devices (PRD's)) were not utilized.

The tank tested was a 5,000-psig (34.5-MPa) Type-IV hydrogen cylinder approximately 33 in. (84 cm) long with a 16-in. (41-cm) diameter (outer dimensions) and weighed approximately 70.6 lb (32.0 kg). The cylinder was comprised mainly of a high-density polyethylene inner liner, a carbon fiber structural layer, followed by a fiberglass protective layer. Each end of the cylinder consisted of a dome and an aluminum end fitting.

Figure 3. Hydrogen Fuel Tank in Bonfire Test Fixture

The test setup for the bonfire test is shown in Figure 3. The hydrogen tank was supported by two insulated chains approximately 24 in. (61 cm) apart. A line burner provided the propane fueled heat source below the tank. The line burner was approximately 12 in. (30 cm) wide and has an effective length of 33-in. (84-cm). The burner length was shorter than the 65 in. (165 cm) required by the standard. This was done to determine the effect of a concentrated bonfire on the hydrogen tank. The line burner was protected from wind with a 32 x 90 x 8-in. deep (81 x 230 x 20-cm) pan.

The tank instrumentation included an internal thermocouple and pressure transducer. The flame exposure temperatures and tank surface temperatures were measured by six thermocouples. Overpressures around the tank were measured by four blast-wave pencil probes.

The composite material on the surface of the tank ignited approximately 45 seconds into the test. After 6 minutes and 27 seconds, the cylinder catastrophically failed through the bottom , launching the 30.9 lb. (14.0 kg) main portion 270 ft. (82 m) east of the test location. Blast pressures to the west were 43psi (300 KPa) at 6.3ft. (190 cm.) and 6 psi (41 kPa) at 21.3 ft. (650 cm.).

The internal temperature and pressure of the hydrogen at the time of failure was 103°F (39°C) and 5,180 psig (35.7 MPa), respectively. In this experiment, the pressure inside the cylinder did not rise sufficiently so that a pressure-activated pressure relief device would have activated to prevent rupture. The temperature inside the cylinder also did not climb sufficiently to activate a thermally-activated pressure relief device if it used the *internal* temperature as the temperature source. It is necessary to place PRDs such they see the same, or worse, fire as the tank. Redundancy may be prudent also.

FIRE SAFETY ISSUES IN 42-VOLT APPLICATIONS

Major auto manufacturers are currently developing electrical systems that operate on 36-volt architectures, transitioning from the current 12-volt systems (14 volts when charging) typically used today. The 36 volt architecture charges at 42 volts, with possible voltage peaks as high as 58 volts.

Carbon Tracking.

MVFRI and USCAR jointly funded research on DC carbon tracking of plastic materials used as connectors and insulators. [Wagner, 2003, Wagner, 2004]. This effort developed a DC test procedure and evaluated 24 candidate plastic materials. A wide range of performance was exhibited by these materials. Twelve tests were highly instrumented and provided some insight into the physics of the carbon tracking phenomenon [Stephenson, 2005].

The electrical conductivity of common underhood fluids was also measured to see if they might induce carbon tracking [Dey, 2004]. It was found that the electrical conductivity of these fluids was too low to be a concern.

High Intensity Arc Flammability.

Even at 14-volts, there are fires caused by shorts and other malfunctions in the electrical systems. As was shown previously in the data analysis, more fires occur in frontal impacts, and initiate within the engine compartment.

If a circuit is broken with a 14-volt circuit, some sparking may occur, but not a sustained arc. With a 42-volt system there is likely to be a sustained arc when a circuit opens or there is a short to ground. This arc has tremendous power associated with it. It can easily produce 1000 Watts of power. The temperature of the plasma can be 6000 C. This level of power can ignite most materials and can burn holes in sheet steel.

MVFRI and USCAR are currently sponsoring an effort on Arc Flammability at Underwriters Laboratories. A DC arc testing machine is currently being developed. 75 materials, including several underhood fluids, will be tested. Results are expected before the end of 2005.

Battery Abuse Testing.

Since batteries are typically mounted in the underhood region of the vehicle, and most of the under-hood fluids are flammable (including the engine coolant and windshield washer fluid), there is reason to suspect that the battery may contribute to many under-hood fires. Batteries contain a great deal of energy (~ 3 million Joules for an 85 Ampere-hour battery). A short can dissipate hundreds of Watts, and can ignite surrounding flammable materials. A crushed battery can create either external or internal shorts and begin a heat release that can ignite the plastic battery case, and then spread to other under-hood materials.

We have contracted with SwRI for abuse testing of 36-volt batteries and comparable 12-volt batteries.. The batteries will be tested using several of the test procedures in SAE Standard J 2464 "Electric Vehicle Battery Abuse Testing," The tests to be conducted will be the penetration, crush, radiant heat, and short circuit tests. Preliminary results have not shown any significant energy releases or flaming from the battery. The final report will be available by summer 2005.

CONCLUSIONS

Analysis of fire involved crashes from state data, NASS/CDS and FARS all show that frontal crashes are associated with the majority of both major and minor fires. Fires in rollovers are less numerous than fires in frontal crashes, but the fire risk is higher. Based on FARS cases, the risk of a fire in a rollover is 78% higher than for the other crash modes. In NASS/CDS, rollovers are the most frequent crash mode that is associated with fuel tank fires.

The most frequent source of both major and minor fires is the engine compartment. Eighty percent of the fires in frontal crashes and 67% of the rollover fires begin in the engine compartment.

About 25% of the FARS crashes where fire is the most harmful event also involve entrapment. Ninety –eight percent of these cases are coded as having the highest severity of damage. NASS/CDS data indicates that internal entrapment occurs in about 5% of the cases with fires and entrapment by doors jammed occurs in about 1.3% of the fire cases. However, in all NASS cashes, the approximately 50% of the occupants coded as entrapped are in cashes with severity less than 17 mph in frontals, 16 mph in side impacts and 20 mph in rear impacts.

The fire rescue times reported in NFIRS are longer for the rural than for urban crashes. For rural crashes, 75% of the time the arrival on scene occurs within 10 minutes from receipt of the call. FARS records the time from the crash to arrival of rescue. For rural crashes 75% time the rescue is within 24 minutes of the crash.

Analysis of fire tests of crashed vehicles showed that the passenger compartment became untenable within 3 minutes of flame penetration. In the tests to simulate a fuel pool fire, the flame penetration time into the passenger compartment varied between 0.5 to 3.0 minutes. For under-hood fire tests, flame penetration time into the passenger compartment varied between 10 to 24 minutes.

A typical compressed hydrogen tank, when exposed to a bonfire, presents safety challenges. The consequence of a rupture is catastrophic. In our test, blast pressures of 6 psi were measured 21 ft away from the tank, and debris was propelled more than 250 ft. The tank composite material began to burn after being exposed to the bonfire for 45 seconds. At the time of tank rupture, the pressure inside the 5,000 psi tank had only increased by 180 psi and the temperature had risen to 103 ^{o}F. The bonfire protection and pressure relief sensing for hydrogen tanks will require sophistication to insure the internal pressure is released prior to tank rupture..

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