NHTSA'S FOUR-YEAR PLAN FOR HYDROGEN, FUEL CELL AND ALTERNATIVE FUEL VEHICLE SAFETY RESEARCH

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ABSTRACT

The National Highway Traffic Safety Administration's (NHTSA's) program for hydrogen, fuel cell, and alternative fuel vehicles is focused on providing critical safety information on hydrogen-powered fuel cell and internal combustion engine (ICE) vehicles. Safety information is vital to support the launch of the FreedomCAR Program, a cooperative automotive research partnership between the U.S. Department of Energy (DOE) and the U.S. Council for Automotive Research (USCAR), whose members include Ford Motor Company, General Motors Corporation, and DaimlerChrysler Corporation. FreedomCAR was announced in January 2002 by Energy Secretary Spencer Abraham, and is designed to advance the development of fuel cell vehicles and hydrogen fuel infrastructure. The program was initiated as part of the President's goal to reduce U.S. dependence on foreign oil, improve vehicle efficiency, and reduce vehicle emissions. The President's Hydrogen Fuel Initiative, announced in 2003, expands on the FreedomCAR Program to make fuel cell vehicles a practical and cost-effective choice for large numbers of Americans by 2020. The President's proposed federal budget for fiscal year 2006 includes tax incentives for the purchase of fuel cell vehicles. NHTSA's safety initiative will complement these efforts by conducting risk assessment studies of hydrogen fueled vehicles, and developing test and evaluation procedures for safety assessment using suitable performance criteria. The risk assessment studies will quantify potential failures that could indicate unsafe conditions.

Corollary efforts by NHTSA address fuel economy and international harmonization of global technical regulations (GTR) for hydrogen vehicles. The agency will assess gasoline equivalency for fuel cell vehicles, and analyze potential increases to fleet fuel economy. NHTSA will also work with its international counterparts to determine the content of regulations pertaining to fuel cell and internal combustion engine (ICE) hydrogen vehicles.

This paper describes the safety issues that have been identified as unique to hydrogen-powered vehicles and the approach and timeline that NHTSA will pursue to address these issues.

INTRODUCTION

Ensuring that hydrogen ICE and fuel cell powered vehicles provide a level of safety comparable to that of other vehicles currently in use in the United States requires a substantial research effort. Hydrogen-powered vehicles will utilize many advanced and unique technologies that have not been tested in the transportation environment. Many manufacturers, however, are substantially investing in producing and marketing these vehicles in the near future. Very little data are available concerning their safe performance because so few exist; they are typically prototypes handled by specially trained personnel. As these vehicles are deployed in the fleet, the safety of hydrogen as a fuel and the safety of alternative fuel vehicles in crashes becomes an issue of significant concern. A failure to adequately address safety concerns in the earliest stages of development could have a negative impact on the deployment of this new technology.

APPROACH

Following the announcement of the FreedomCar program in 2002, NHTSA began collecting information on the status of hydrogen vehicle technology and drafting a plan to address hydrogen and fuel cell safety for passenger vehicles.

An agency-wide working group was established to coordinate activities in the areas of international harmonization, research, regulation, and enforcement relative to hydrogen fueled vehicle safety. This group also coordinates activities with the Department of Transportation (DOT) Hydrogen Fuels Working Group, which consists of representatives from all modes of DOT, and with the Department of Energy, the FreedomCar and Fuels Codes and Standards Technology Team, and the Office of Science and Technology Policy's Hydrogen and Fuel Cell Interagency Task Force.

In the fall of 2002, NHTSA began meeting with vehicle manufacturers to discuss hazards, risks, and safety considerations particular to hydrogen-fueled vehicles. As of January 2005, NHTSA had met with five manufacturers to discuss these issues. In June 2004, NHTSA obtained clearance from the Office of Management and Budget to send a letter to ten vehicle manufacturers requesting that they voluntarily provide written information on their safety strategies. In July 2004, NHTSA published its research plan, which was developed in part from the interchange conducted with industry over the previous year and a half, in the Federal Register for public comment. These documents, and the manufacturer and public responses to them, may be downloaded from the DOT docket. [1]

PROBLEM DEFINITION

The unique safety challenges presented by hydrogen and fuel cell vehicles fall into four broad categories:

First, the characteristics of hydrogen as an energy carrier differ from those of conventional vehicle fuels like diesel and gasoline. Hydrogen also has unique handling requirements, as compared to other alternative fuels, such as natural gas (CNG). Hydrogen is colorless, odorless, burns without producing a visible flame or radiant heat, and is difficult to contain. It has a minimum ignition energy an order of magnitude lower than that of other hydrocarbon fuels (.02 millijoules) and a much wider flammability range (4 to 75 percent volume in air). The quenching gap, which is the largest passage that can prevent flame propagation when filled with a flammable mixture, is smaller than that of methane, propane, and gasoline, requiring tighter tolerances to prevent flame propagation. Unlike CNG, hydrogen can cause significant deterioration in fuel system components by diffusing into steel and other metals, causing a phenomenon known as "hydrogen embrittlement." As a result, the metal will break or fracture at a much lower load or stress.

Second, hydrogen storage methods are different from storage methods for other fuels. One of the main safety concerns is the safe onboard storage of hydrogen. There are a variety of very different technologies used for storing the hydrogen fuel, from very high pressure gas storage, to cryogenic liquid, solid metal hydrides that require complex thermal management systems for charging and discharging hydrogen, liquid chemically bonded forms that produce highly alkaline spent fuel waste, and on-board reformulation systems that produce the hydrogen from hydrocarbon fuels. High-pressure storage carries the risk of fuel tank rupture and missile damage. Liquid hydrogen is cryogenic (-253 degrees Celsius) and requires special tanks, insulation, and venting systems, to maintain liquid conditions. The hazard from a leak or spill is the potential for cryogenic burns and fires.

Third, fuel cells are electrical devices, but they operate differently than batteries, which are power storage devices. Fuel cell vehicles operate at high voltage, and in some cases are equipped with auxiliary propulsion batteries, so that the issues of electrical shock, isolation, and ignition of surrounding materials such as plastics must be studied as well.

Finally, passenger compartment integrity and crush zone design in hydrogen and fuel cell vehicles may be tied to a significantly different mass distribution and stiffness than that of current conventional vehicles. An analysis and forecast prepared by the Massachusetts Institute of Technology compares a 1996 baseline vehicle to 11 advanced vehicle designs with varying drivetrain options projected for MY 2020 and concludes that overall vehicle weight will not be reduced, but propulsion systems will be heavier and structural and body components will be lighter [2]. The volumetric envelope of the propulsion system components will differ as well, and 4 different packaging options have been identified that alter the mass distribution when compared to vehicles today [3].

OBJECTIVES

The objective of this research program is to ultimately ensure that hydrogen and fuel cell vehicles attain a level of safety equivalent to that of conventionally fueled vehicles. Current Federal motor vehicle safety standards (FMVSS) for fuel system integrity do not address the unique characteristics of hydrogen and fuel cells discussed in the previous section. Industry and government codes, standards, and regulations are still in the very early stages of development and would benefit greatly from real world risk assessment. Similarly, development of test procedures and suitable performance criteria are critical in order to quantify potential failures and resulting unsafe conditions as these vehicles are operated in the real world.

CURRENT BASELINE STATUS OF HYDROGEN-POWERED VEHICLES

A report published in February 2004 by the Department of Energy identifies over sixty passenger vehicle models (1994 – 2003) fueled by hydrogen [4]. Although many of these vehicles can be classified as experimental or concept vehicles, some are production prototypes, in use in demonstration fleets and available for public ride-and-drive events. These vehicles range from compacts to minivans to SUV's. Fuel storage options are onboard reformulation of gasoline or hydrocarbon fuels, high-pressure compressed hydrogen, cryogenic liquid hydrogen, sodium borohydride, and metal hydrides. Vehicles may have additional batteries or ultracapacitors to buffer power delivery.

Honda has a production prototype vehicle, the FCX, on the road in California that is self-certified as meeting all existing FMVSS and has been crash tested in front, offset, side and rear crash modes without failure of the fuel system or occupant protection requirements. The vehicle incorporates several safety features not required by current FMVSS. If any front, side or rear impact is severe enough, the control unit automatically shuts off the flow of electricity from the fuel cell module and the capacitor module. In less than a second, there is no current in the high voltage cables. Each hydrogen tank contains three internal safety valves. One prevents backflow of hydrogen during refill, another shuts off flow of hydrogen when signaled by the power control unit, and the third is a temperature activated relief device designed to release all hydrogen through a line and out the back of the vehicle until the tanks are empty, which could take up to five minutes if the tanks are full. In addition to the in-tank safety valves, several sensors are located along hydrogen lines to detect any possible leak. If a leak is detected, the power control unit stops the flow of hydrogen from the tanks. The vehicle is also equipped with a manual shut-off valve inside the right wheel well. NHTSA will need to test these safety systems and determine whether regulations specifying performance criteria are required. The Japanese government intends to have regulations in place in 2005 addressing the safety of these vehicles, with a commercialization goal of 2010.

NHTSA'S RESEARCH PLAN AND RELATED ACTIVITIES

Subject to the availability of research funds through the Department, NHTSA will continue to develop research plans and begin program implementation in FY 2005. This program will have several elements:

Outside Activities

Review and or participate in development of applicable industry codes and standards, public outreach, and safety information collection.

National/International Voluntary Standards Organizations, Codes and Standards

- NHTSA reviewing Society of Automotive Engineers (SAE) Recommended Practices J2572, J2578, J2579, J2600, J2601.
- NHTSA reviewing Canadian Standards Association (CSA) America HGV standards.
- NHTSA participating in International Organization for Standardization (ISO) activities.

Expand Outreach to the Public Safety Community

Obtain input and feedback from first responder experts from the fire service, emergency medical service, traffic law enforcement and involve public safety professionals in formulation, development, and post-implementation evaluations of codes and standards.

Information Collection

Collect real world safety performance and vehicle specification data from:

Demonstration vehicles -

- DOE demonstration program
- DOT/Federal Transit Administration bus demonstration program – Three 30-foot fuel cell test-bed buses were developed in conjunction with DOE, and work on two 40-foot transit buses has begun.
- California Fuel Cell Partnership program – Collaboration between vehicle and equipment manufacturers, fuel suppliers, and government to prepare the market for commercialization of fuel cell vehicles.
- EPA/DaimlerChrylser/UPS Fuel Cell Delivery Vehicle Initiative, announced May 2003. Collaborative project in which UPS will operate package delivery vehicles powered by hydrogen fuel cells supplied by DaimlerChrysler, beginning late 2003 and continuing in 2004. The EPA will supply a hydrogen refueling station at its Ann Arbor facility. This is the first use of fuel cell technology in a commercial delivery fleet in North America.
- California South Coast Air Quality Management District - Development and demonstration of vehicles with ICE using hydrogen fuel and development of 5 hydrogen refueling stations.

- General Motors' Washington DC fuel cell preview program launched in May 2003, is a Washington-based fleet of hydrogen-powered vehicles providing up to 10,000 test-drives of GM's HydroGen3 fuel cell prototype, fueled by the nation's first hydrogen station. The two-year program will provide test drives for legislators, regulators, environmentalists, and other policy makers.
- General Motors' HydroGen3 vehicles will operate in FedExpress service in Tokyo, Japan.
- Toronto City and Hydrogenics Corporation three-year project demonstrating hydrogen and fuel cell technology for mobile and stationary power.

Manufacturer data -

- Follow manufacturer development of hydrogen and fuel cell vehicles (BMW, DaimlerChrysler, Ford, General Motors, Honda, Hyundai, Mazda, Nissan, Toyota, Volkswagen)

Vehicle Safety Research

Powertrain, vehicle fuel container, and delivery system performance testing (vehicle or fuel system mockup)

Effectiveness of safety systems:

- Evaluate performance of pressure relief devices, thermal and electrical management systems for tanks, fuel cells and batteries, purging of fuel cell and lines, and discharge of residual voltage in fuel cell stack.

Leak Detection:

- Measure hydrogen leakage and concentrations in and around fuel system over time. Test passive vs. active ventilation systems.
- Determine suitable surrogate for hydrogen that is safe for leak detection and vehicle crash testing program.

Fire Exposure:

- Conduct vehicle buck ignition and flammability tests through controlled releases of hydrogen and electrical arcs at various severed locations in tubing between onboard storage tanks and fuel cell stack. Using a vehicle underbody buck, conduct pool fire testing, similar to the ECE-R34 test for plastic fuel tanks for gasoline.
- Conduct material flammability tests with a hydrogen flame.
- Conduct self-ignition tests to determine if external debris or particulate matter can cause ignition of venting hydrogen.

Road hazards exposure:

- Conduct tests to determine vulnerability of components/packaging to road debris.

Refueling system performance testing

Leakage:

- Conduct tests to monitor hydrogen leakage from vehicle/fueling system interface.

Spark/grounding:

- Evaluate static electricity/spark suppression mechanisms on vehicle and fueling station.

Full vehicle performance testing

Crash:

- Run series of crash tests to determine compliance and/or obstacles to compliance with Federal Motor Vehicle Safety Standards (FMVSS) 208, 214, 302, and 305.
- Determine comparable areas of fuel system integrity not covered under existing FMVSS 301, 303, and 304.

Leakage:

- During operation and while parked, measure hydrogen leakage and concentrations inside and outside the vehicle over time. Test passive vs. active ventilation systems and performance of recovery or conversion systems to remove hydrogen.

Electrical isolation of fuel cell, cooling system and auxiliary batteries:

- Conduct tests to determine electrical isolation of the entire high voltage system and its components (fuel cell, batteries, cooling system) pre- and post crash and after several charge/discharge cycles of the propulsion system.
- Determine appropriate safety factor for electrical isolation for fuel cells, battery packs, ultra capacitors and other electrical, high-energy storage devices (current requirement under FMVSS 305 is 500 ohms/volt). (NOTE: Some manufacturers indicate that this level is not attainable in certain systems.)

Incident Management:

- Determine any special post crash handling requirements for vehicle occupants, public safety personnel, towing, storage, or disposal.
- Review California Fuel Cell Partnership emergency response guide and other available responder training materials.

Special Crash Investigations Program:

- In-depth investigations of any real world incidents.

Recycling:

- Coordinate with EPA and identify toxic/hazardous materials used in the manufacture of vehicles.

Corporate Average Fuel Economy (CAFE) analysis and evaluation:

- Determine appropriate gallon equivalent of hydrogen. NHTSA is statutorily required to set hydrogen gasoline gallon equivalency (GGE) factors by the Alternative Motor Fuels Act, as amended. In 1996, NHTSA issued a final rule entitled "Manufacturing Incentives for Alternative Fuel Vehicles" (49 CFR 538.8), establishing a GGE value for internal combustion engine (ICE) hydrogen vehicles. NHTSA is in the process of determining the applicability of the hydrogen ICE equivalency value to hydrogen fuel cell vehicles.

- Assess hydrogen vehicle fuel economy levels. Since the agency is required to set fuel economy standards at the maximum feasible level for each model year, it is necessary for the agency to investigate and analyze the potential increases in fuel economy attributable to hydrogen vehicles. To accurately project fuel economy increases, NHTSA must understand the critical path of various fuel cell designs, and the technological challenges manufacturers face with each model.
- Review work by Japan Automobile Research Institute (JARI) and others to determine appropriate methodology to utilize for hydrogen fuel economy measurement during fuel economy testing.

International Regulations/International Policy and Harmonization

Assess need for regulation based on research test results and safety performance of passenger cars, multipurpose vehicles, trucks, and buses.
- Goal- Development of performance based Global Technical Regulations (GTR) for Hydrogen/Fuel Cell Vehicles.
- Participation in the UN/Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulations (WP.29) Hydrogen/Fuel Cells Working Group.
- Cooperation with Canada, the European Union and Japan on the development of safety regulations for hydrogen fueled vehicles under bilateral cooperative agreements with those regions. Identify best safety approaches and conduct joint research and testing.
- Cost, weight and lead time impacts of alternative fuel vehicles

RESEARCH TIMELINE

Tables 1 – 5 provide the timeline that will be followed in assessing the safety performance of hydrogen, fuel cell and hybrid vehicles (i.e., those using auxiliary batteries or ultracapacitors) and subsystems. Availability of test vehicles, components and hydrogen fueling stations is critical to the success of this assessment. Current costs for hydrogen-powered vehicles exceed $1,000,000 per unit. Fuel cell stacks for vehicles range in price from $250,000 to $1,000,000. NHTSA is working closely with manufacturers and other stakeholders in the hydrogen economy to cost share resources and testing through cooperative agreements, and by "piggy-backing" safety testing onto other programs. For example, manufacturers may provide vehicles in order to share the cost of testing, or demonstration fleets may provide "retired" vehicles for testing prior to disposal.

The results of this assessment may be used as input to regulations (GTR, FMVSS) that minimize the potential for harmful events or outcomes caused by loss of fuel system integrity.

The following timelines are proposed and subject to change:

Table 1. Component level testing – Powertrain, vehicle fuel container, delivery system performance testing (tanks, or fuel system mockup)

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
1.1) Determine suitable surrogate for hydrogen that is safe for leak detection and vehicle crash testing (Helium or Nitrogen?)	√			
1.2.) Destructive testing of (a) compressed and liquid H2 tanks	√	√		
(b) Other hydrogen storage Similar to FMVSS 304 testing			√	
1.3.) Evaluate methods for leak detection	√			
1.4.) Evaluate thermal and electrical management systems for fuel cells, batteries, ultracapacitors		√	√	

1.5.) Evaluate effectiveness of safety systems for shutting down hydrogen flow, strategies for controlled and rapid release of hydrogen (venting and blowdown), purging of fuel cell and lines	√	√		
1.6.) Fire Exposure –				
(a) Vehicle buck ignition and flammability through controlled release of hydrogen, electrical arcs				√
(b) Pool Fire – ECE-R3 test		√		
(c) Material flammability				√
(d) Autoignition testing			√	
1.7) Road Hazards Exposure Vulnerability of packaging/ components road debris				√

Table 2. On board refueling system performance testing – Conduct tests on up to 35 identified vehicle platforms, fueling station architecture currently unknown – Identify and test at available fueling stations.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
2.1) Evaluate communication to prevent overpressure, leakage	√	√	√	√
2.2) Evaluate effectiveness of spark suppression/grounding	√	√	√	√

Table 3. Full vehicle performance testing – Conduct crash, static pre and post-crash hydrogen leakage, electrical isolation tests, develop post -crash handling/EMS procedures. Coordinate with EPA on recycling issues. Destructive testing on 3 vehicles per year, non-destructive testing on available demonstration vehicles. Assume cost share with manufacturer or other stakeholder.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
3.1) Crash - Procure at least one representative vehicle model per year and conduct front, side rear occupant protection and fuel system integrity crash tests (FMVSS 208, 214, 300 series - requires 3 vehicles per test series)	√	√	√	√
3.2) Leakage - Measure/monitor during operation while parked/garaged test active ventilation systems and performance of H2 recovery or conversion systems	√	√	√	√

3.3) Electrical Isolation of high voltage systems pre post crash, charge cycling, determine appropriate safety factor for isolation (currently 500 ohms/volt	√	√	√	√
3.4) Incident Management – Vehicle, occupants, public safety, towing storage, disposal	√	√	√	√
3.5) Special Crash Investigations	√	√	√	√
3.6) Recycling – Coordinate with EPA	TBD			

Table 4. Corporate Average Fuel Economy (CAFE)

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
4.1) Corporate Average Fuel Economy (CAFE) – Hydrogen measurement, gallon equivalency, rulemaking requirements	√	√	√	√

Table 5. International harmonization of codes and standards, development of Global Technical Regulation for hydrogen fueled vehicles

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
5.1) Representation at UNECE WP 29 (GRPE) - Comparative testing of European and Japanese requirements - Develop global technical regulation	√	√	√	√
5.2) Cost, weight, and lead time impacts of alternative fuel vehicles		√	√	√

CONCLUSIONS

Following NHTSA’s discussions with vehicle manufacturers and participation with the UN/Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulations (WP.29) Hydrogen/Fuel Cells Working Group, research in support of draft and adoption of global technical regulation should be completed within the next three to four years for manufacturers to be able to initiate mass production of hydrogen vehicles around 2010. With that timeline quickly approaching, the supporting research, if pursued aggressively and collaboratively with other interested parties to a completion in 2008-2009, could result in adoption of a GTR in 2010-2012.

REFERENCES

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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 °C for a minivan to a high of 550 °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.

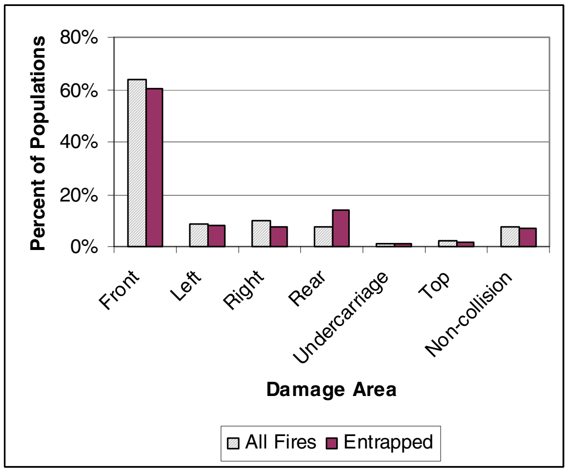

Figure 1. Percentages of Crashes with Fire as the Most Harmful Event and Percentages of Crashes with both Fire as the Most Harmful Event and Entrapment by Vehicle Damage Area

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.

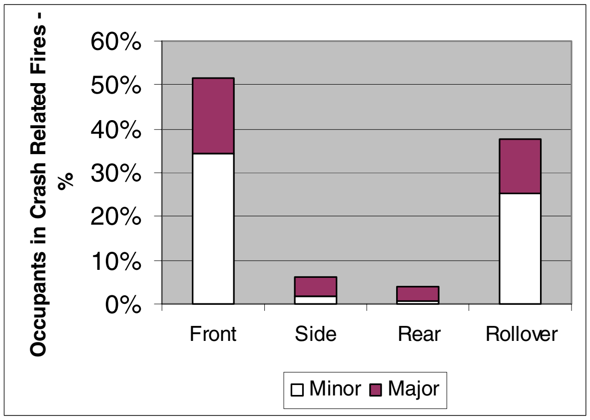

Figure 2. Occupants in Crash Related Fires by Crash Mode and Fire Severity from NASS/CDS 1994-2002.

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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CFD SIMULATION OF DIFFUSION OF HYDROGEN LEAKAGE CAUSED BY FUEL CELL VEHICLE ACCIDENT IN TUNNEL, UNDERGROUND PARKING LOT AND MULTISTORY PARKING GARAGE

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ABSTRACT

Hydrogen fuel cell vehicles are expected to come into widespread use in the near future. It is therefore important to predict whether risks from hydrogen leaked caused by accident in semi-enclosed area can be avoided. In this study, CFD simulation was carried out for hydrogen leakage in typical tunnels, underground parking lot, and multistory parking garage. Simulation scenarios were as follows. The hydrogen leak rate was chosen to be the equivalent energy of allowable gasoline fuel leak in a vehicle collision test, as prescribed in FMVSS301. The ventilation rate was zero for the case of tunnels, and air exchange rate was zero or ten times per hour for underground parking lots. The analytical periods were thirty minutes for all cases. It can be said that the area of flammable mixture was limited that close to the hydrogen leaking vehicle even when there was no ventilation and become smaller when the ventilation exists. The results would therefore indicate that safety was maintained in cases of hydrogen leakage in the semi-enclosed areas even with existing equipment.

INTRODUCTION

Recent years have seen an advance in global warming due to carbon dioxide and other emissions, and various approaches are being investigated to suppress these emissions. One approach is to promote to cleaner emissions from automobiles, which use mainly fossil fuels. Another approach is the development of fuel cell vehicles, which use hydrogen instead of fossil fuels as an energy source.Fuel cell vehicles have attracted much attention as clean cars with no harmful emission gases. Today, various public and private organizations are conducting driving tests on public roads of fuel cell vehicles produced by major automakers in each country, and collecting data to be used in developing these vehicles for the commercial market. To promote the use of these vehicles, Japan is today reviewing its relevant laws and regulations. Before regulations can be revised, however, it is necessary to investigate the safety of fuel cell vehicles during accidents.

In the present study, tunnels, an underground parking lot, and a multistory parking garage were chosen as semi-enclosed spaces where fuel cell vehicles would be driven and stored. Safety of hydrogen leakage in such spaces was investigated. The purpose of the present experiment was to predict whether leaking hydrogen would pose a danger to the selected facilities. Specifically, we wanted to investigate the diffusion of leaking hydrogen in semi-enclosed spaces, where it accumulates in those spaces, the behavior in which it accumulates, and the region above the lower flammable limit.

SUBJECTS OF ANALYSIS

Tunnel

Two tunnel shapes were chosen for the present study. To simulate a long tunnel we selected a cross-sectional configuration with a 2% uniform rising and downing longitudinal slope, and to simulate an underwater tunnel one with a 5% uniform trough longitudinal slope [1]. The space for analysis was limited to a length of 50 m. Tunnel width was 10 m, and tunnel height was 7 m for the long model tunnel and 4.5 m for the underwater model tunnel. Both model tunnels were considered to have one way direction road with 2 lanes. The hydrogen leakage was from a fuel cell vehicle driving in the tunnel, resulting from a collision or other accident. The leak occurred in the middle of the tunnel with the vehicle stopped. The vehicle with the hydrogen leak was in the passing lane, followed by 4 other vehicles. Thus, there was a total of 5 vehicles in the tunnel. This calculation was done under a condition of no ventilation. Figure 1 shows a cross-section of the 2 model tunnels.

Analyses were done for the following 3 cases.

Case T-1: Long model tunnel

Case T-2: Underwater model tunnel

Case T-3: Long model tunnel (length 200 m)

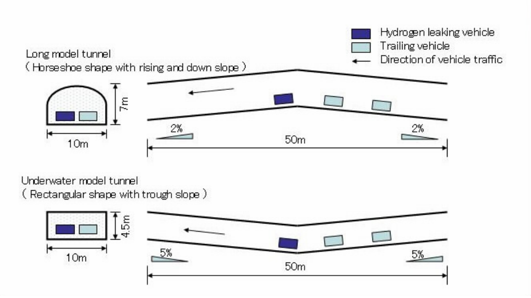


Figure 1. Tunnel configuration.

Underground Parking Lot

A general self-parking underground parking lot [2] was adopted as the configuration for analysis. One section from among all the areas of the parking lot was taken as the area for analysis. This section was one with 9 vehicles each in 2 rows, a total floor area of 480 m^2 and ventilation equipment. This area was subject to the requirement for underground parking lots with a floor area of greater than 500 m^2 to have air exchange at least 10 times/h (Fire Defense Law enactment order).

The parking lot had air duct to the road, and was equipped with emissions ducts in the parking areas. And the number of air exchanges per hour was set at 0 times/h (assuming equipment failure) and 10 times/h. The hydrogen-leaking vehicle was located in the middle of the 9 vehicles; in other words, some distance from the entrance and exit. Figure 2 shows the arrangement of the vehicles in the underground parking lot.

Analyses were done for the following 3 cases.

Case U-1: Air exchange 10 times/h

Case U-2: No air exchange

Case U-3: No air exchange (2 leaking vehicles)

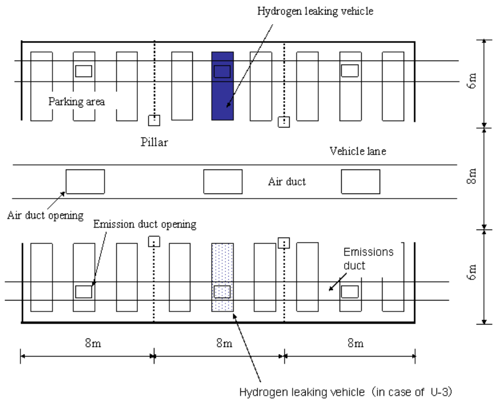


Figure 2. Configuration of underground parking lot.

Multistory Parking Garage

The configuration adopted for analysis was an elevator parking tower [3], which are commonly seen in Japan in recent years (432 in operation in 2001). The frontage of the parking garage is 6.5 m x 7.5 m in depth x 30 m in height. The garage holds 24 vehicles (12 vehicles x 2 rows). Vehicles enter and exit this parking garage through a ground floor opening that directly faces the outside atmosphere, and there is an emissions louver (ventilation hole) near the ceiling. The location of the vehicle leaking hydrogen was set as an analysis parameter, with the 2 locations of the lowest and the second from highest positions. Figure 3 shows the location of the vehicles in the multistory parking garage.

The following 3 cases were selected for analysis.

Case M-1: Leaking vehicle on the lowest level

Case M-2: Leaking vehicle on the second from highest level

Case M-3: Leaking vehicle on the lowest and the second to highest levels (2 leaking vehicles)

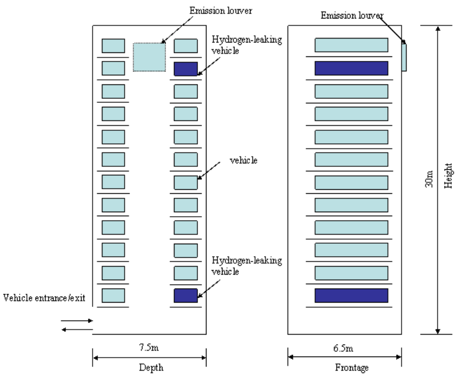


Figure 3. Schematic representation of multistory parking garage.

NUMERICAL SIMULATION METHOD

Simulation Scenario

The number of vehicles leaking hydrogen was set at 1 or 2 for the tunnel, underground parking lot, and multistory parking garage. The vehicles were given a linear configuration with dimensions of 4.7 m x 1.8 m x 1.7 m. The hydrogen leak rate was set at 133 L/min (20°C), which is the energy equivalent of the allowable gasoline leak and prescribed in the "Fuel system integrity" of U.S. federal automobile safety standard FMVSS301. The hydrogen leak rate was considered to be a constant flow during the release period of 30 minutes within the given space. The leaking portion of the vehicle was the boundary surface with a rate of 0.887 m/s, and the leak direction was horizontal from the rear of the vehicle. The leak hole was a square with sides of 0.05 m. The hydrogen did not enter the vehicle passenger compartment.

In an actual fuel cell vehicle, hydrogen gas leaking from the fuel system is sensed and the fuel supply is cut off with an interlock or some other device. Thus, an actual fuel leak can be expected to continue only for several minutes. The present simulation is therefore for a situation more dangerous than an actual occurrence.

Calculation Model

Calculations were done with the general flow modeling software program STAR-CD, using the following calculation model. The governing equation for flow was taken to be a 3-dimensional nonsteady Navier-Stokes equation (continuous, momentum; gravity was considered), and a preservation formula was applied to the concentration site with hydrogen and air shown as mass fractions. The working fluids were standard air and standard hydrogen of 20 °C, in noncompressed flows. The temperature was constant. Table 1 shows the property values used. The turbulence model and other factors used in the calculations were as follows.

·Turbulence model: Standard k-ε model (high Reynold's number, combined with wall functions)
·Turbulence intensity: 10% of main flow at leaking hole
·Turbulence length scale: 5% of leaking hole diameter
·Differencing scheme: third order scheme for convection term (QUICK: Quadratic upstream interpolation of convective kinematics)
·Turbulence Schmidt number: 0.9
·Time interval: 0.2 sec
·Solution method: PISO (Pressure Implicit Split Operator)

Table 1.
Property values of hydrogen and air used

Air	Density	1.204	[kg/m^3]
	Kinematic viscosity	1.50E-05	[m^2/s]
Hydrogen	Density	8.38E-02	[kg/m^3]
	kinematic viscosity	1.05E-04	[m^2/s]
Mutual diffusion coefficient[4]		7.77E-05	[m^2/s]

Mesh

Unstructured mesh (hexahedral mesh) was used for all cases, and the mesh number was approximately 200,000 points in cases of tunnel and multistory parking garage, and was approximately 400,000 points for the case of underground parking lot. A half-model was used for the underground parking lot because of its symmetrical configuration.
The meshes for the tunnel, underground parking lot, and multistory parking garage are shown in Figs. 4, 5, and 6, respectively.

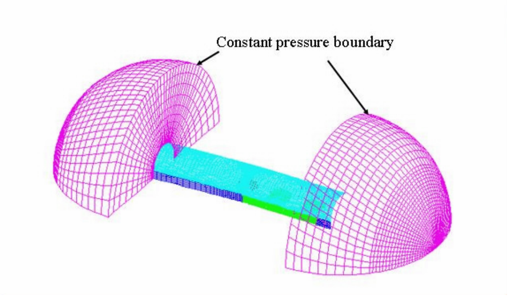


Figure 4. Tunnel mesh (long model tunnel)

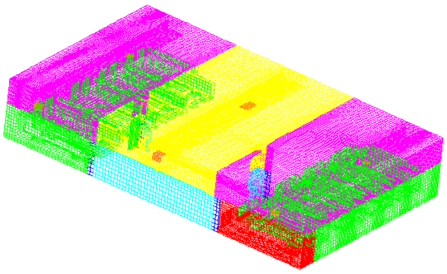


Figure 5. Underground parking lot mesh (half model)

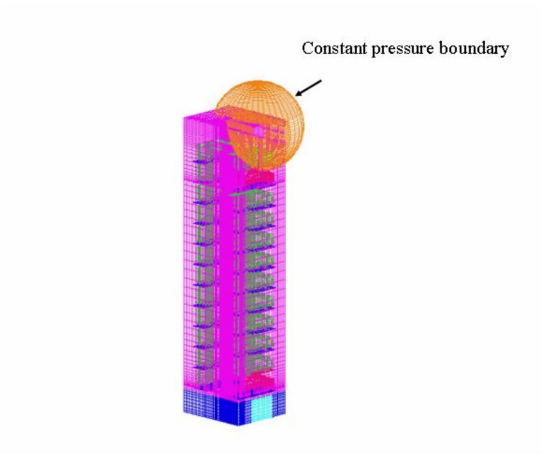


Figure 6. Multistory parking garage mesh

RESULTS AND DISCUSSION

In all cases, the changes with time in hydrogen concentration are shown in a representative cross-section including the hydrogen-leaking vehicle and so on. The hydrogen concentration contour is shown in a total of 14 colors against a blue background. The region above lower flammable limit for hydrogen in air (4 volume %) is shown in red.

Tunnel

Two representative cross-sections including the hydrogen-leaking vehicle for tunnel results are shown in Figure 7.

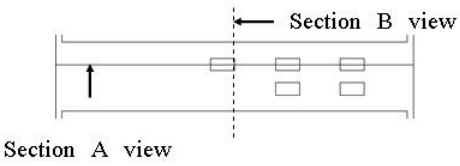
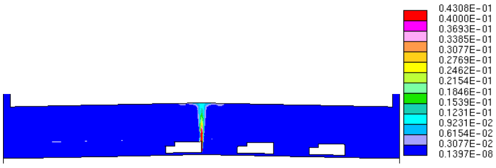


Figure 7. Cross section showing tunnel results (Section A: from side; Section B: from rear).

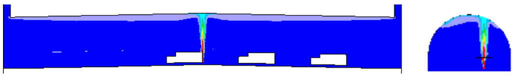
Effects of cross-sectional configuration of tunnel

Figure 8 shows the leaked hydrogen distribution within the long model tunnel simulation in Case T-1.

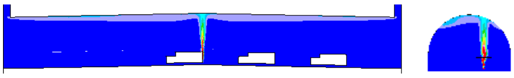
Hydrogen leaking toward the rear from the back of the vehicle has a much lower density than air, so it immediately flows upward. After the leaking hydrogen rises and reaches the ceiling of the tunnel, it mainly disperses in the longitudinal direction. At the point when it reaches the ceiling, the hydrogen concentration is already below the lower flammable limit. The region above the lower flammable limit is restricted to a small area around the source of the hydrogen leak, up to a height of approximately 3 m.



After 20 sec



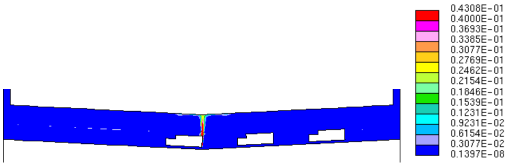
After 600 sec



After 1800 sec

Figure 8. Hydrogen distribution in long model tunnel (left: Section A; right, Section B).

Next, Fig. 9 shows the hydrogen dispersion in Case T-2 simulating the underwater model tunnel. In this case, the upper wall slope of tunnel is upward toward the tunnel before and behind, so the time until the diluted hydrogen reaches the tunnel end is shorter than in Case T-1. This is because the buoyant force of the hydrogen acts in the direction of easy diffusion. After the diluted hydrogen reaches the tunnel end, the hydrogen concentration distribution remains unchanged and constant. Just as with the long model tunnel, the region above the lower flammable limit is restricted to a small area close to the hydrogen leak.



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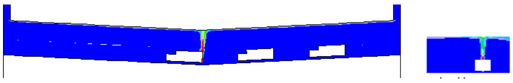


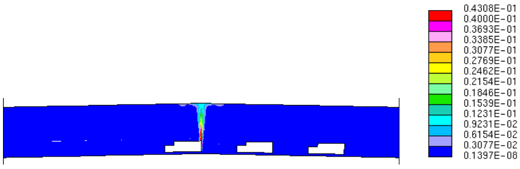
After 1800 sec

Figure 9. Hydrogen distribution in underwater model tunnel (left: Section A; right, Section B)

Influence of tunnel length

To investigate the influence of tunnel length for the long model tunnel, calculations were made for a length of 200 m (Case T-3). The mesh number was approximately

300,000 points. The results are shown in Fig. 10. Because of the long tunnel length, the height of the exits at either end of the tunnel is shorter than in Case U-1, and a thick layer of diluted hydrogen accumulates at the tunnel ceiling. However, as in Case U-1 the region above the lower flammable limit is restricted to a small area immediately next to the hydrogen leak.



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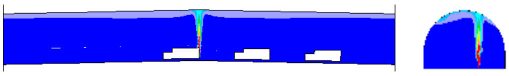

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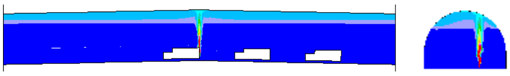


After 1800 sec

Figure 10. Hydrogen distribution in long model tunnel with length of 200 m (50 m section is magnified and shown; left: Section A; right, Section B).

Longer tunnel length is considered to more closely resemble existing tunnels, and there was a greater tendency for accumulation with a tunnel length of 200 m. However, in the case of hydrogen leaks below the allowable level in collisions, it may be possible to enough confirm the effects due to differences in tunnel cross-sectional shape even with a tunnel length of 50 m.

Underground Parking Lot

Two representative cross-sections for underground parking lot results are shown in Figure 11. These are cross sections including the hydrogen-leaking vehicle, and near the ceiling.

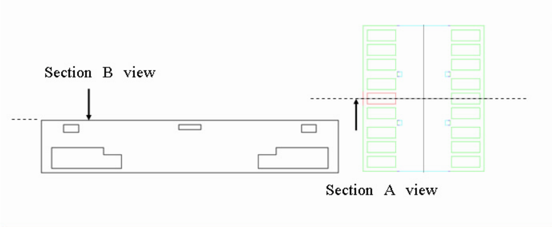
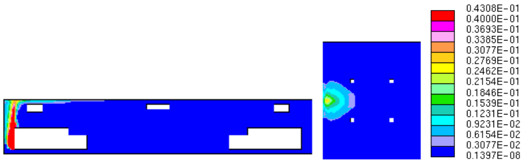


Figure 11. Cross section showing underground parking lot results (left: cross section including hydrogen-leaking vehicle from side (Section A); right: near ceiling at 3.5 m from above (Section B)).

Effects of air exchanges

Firstly, the hydrogen concentration distribution when there is air exchange (Case U-1) is shown in Fig. 12. The flow of hydrogen leaking backward from the rear of the vehicle is deflected upward immediately since hydrogen has a much lower density than air, and rises to the ceiling where it gradually diffuses in a radial pattern. The leaking hydrogen maintains a concentration above the lower flammable limit until it reaches the ceiling at a height of 3.5 m, where it diffuses and becomes diluted to below the lower flammable limit. A portion of the diffused hydrogen is partly drawn into the emissions duct, so almost none of region of diluted hydrogen (0.3 volume%: gray) reaches the vehicle entrance and exit. Moreover, the hydrogen that flows into the emissions duct is below the lower flammable limit. The hydrogen flowing out through the parking lot emissions duct is proportional to that leaking from the vehicle, and it takes about 900 sec to reach a steady state. The region above the lower flammable limit is restricted to a small area directly behind the hydrogen leak.



After 20 sec

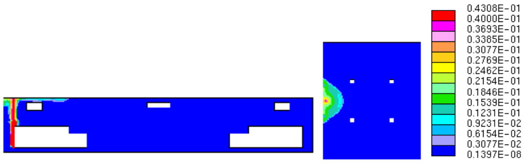
After 120 sec

After 900 sec

After 1800 sec

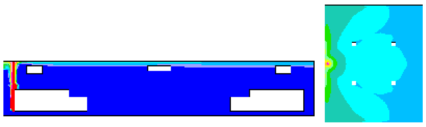
Figure 12. Hydrogen distribution in underground parking lot (Case U-1; left: Section A; right, Section B).

Next, Figure 13 shows the hydrogen concentration distribution when there is no air exchange (Case U-2). The flow of hydrogen leaking backward from the rear of the vehicle is immediately deflected upward because of its low density. It rises to the ceiling and gradually diffuses in a radial pattern after slowly colliding with the wall. That is the same as Case U-1. The region of diluted hydrogen (0.3 volume %) reaches the parking lot entrance and exit about 120 s (2 min) after the start of the leak. The flow out from the parking lot entrance and exit is proportional to the hydrogen leak from the vehicle, and hydrogen distribution condition in area is reached in a steady state after about 1200 s. Even with no ventilation, the region above the lower flammable limit is restricted to a small area immediately next to the hydrogen leak.

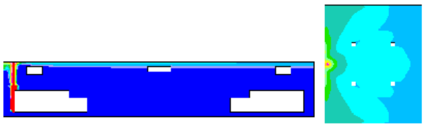


After 20 sec

After 120 sec



After 900 sec



After 1800 sec

Figure 13. Hydrogen distribution of underground parking lot (Case U-2; left: Section A; right, Section B)

Figure 15 shows the changes with time of hydrogen concentration inside the parking lot at various points from the results of Cases U-1 and U-2. Measurements were taken at 3 points just below the ceiling: directly above the leaking vehicle, on the opposite side from the leaking vehicle, and at the entrance and exit on the vehicle side. The hydrogen concentration was lower at all 3 points in the simulation with air exchange than in that without air exchange. The hydrogen concentration at the entrance and exit was decreased from about 1.4 % to below 0.05 %. The hydrogen concentration directly above the hydrogen leaking vehicle decreased from 4 volume % to below the flammable limit.

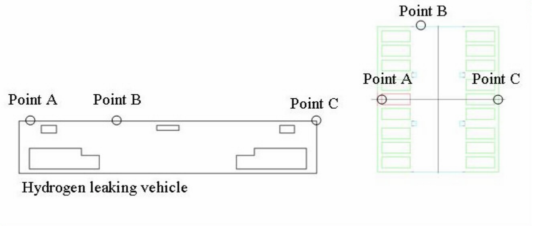


Figure 14. Data collection points on ceiling in underground parking lot (A: directly above hydrogen-leaking vehicle; B: vehicle lane (same side as hydrogen-leaking vehicle); C: opposite from hydrogen-leaking vehicle).

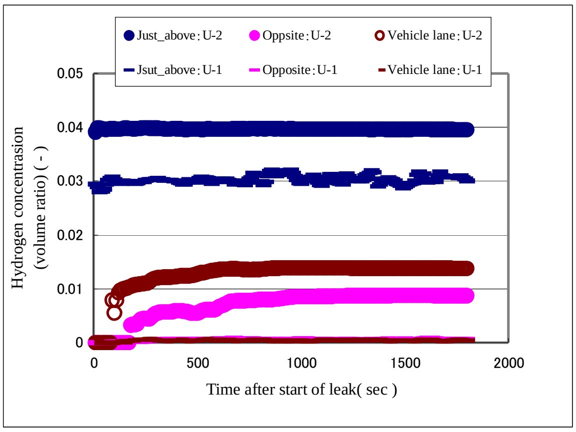
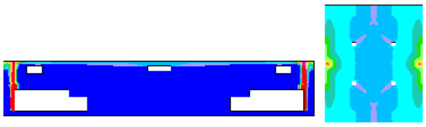


Figure 15. Changes with time in hydrogen concentration at each point on ceiling in underground parking lot (Cases U-1 and U-2)

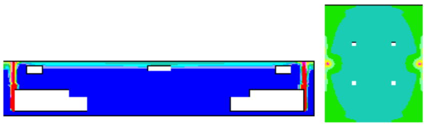
Influence of number of leaking vehicle (1 or 2)

Figure 16 shows results of the hydrogen concentration distribution with 2 leaking vehicles under no air exchange condition. The region of diluted hydrogen concentration near the ceiling is a little thicker because the number of leaking vehicles was increased from 1 to 2. However, the region of hydrogen above lower flammable limit is restricted to around the hydrogen leaks and a very small area on the ceiling above the hydrogen leaks.

After 20 sec



After 120 sec



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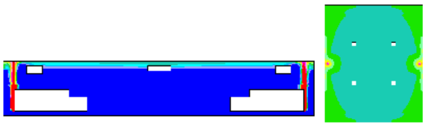


After 1800 sec

Figure 16. Hydrogen distribution in underground parking lot (Case U-3; left: Section A; right, Section B).

Multistory Parking Garage

Figure 17 shows the cross-sectional positions from the results for the multistory parking garage.

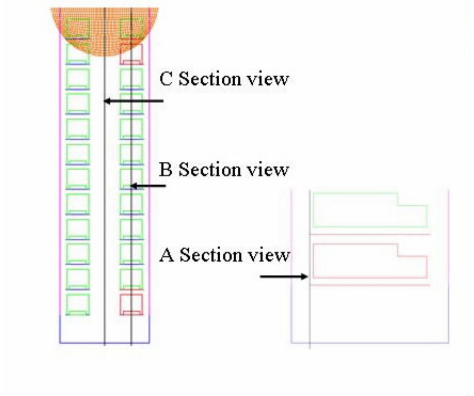
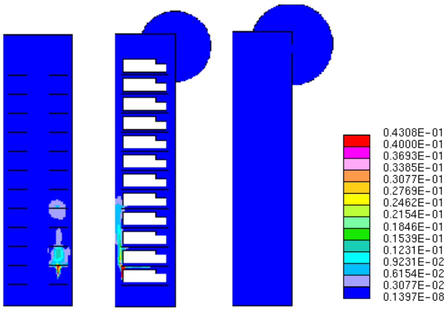


Figure 17. Cross section showing results for multistory parking garage (A: cross section including rear edge of pallet; B: cross section including hydrogen-leaking vehicle; C: cross section of center space in vehicle arrangement).

Influence of leaking position

Firstly, a representative hydrogen concentration distribution when the leak is from a vehicle on the lowest level is shown in Fig. 18. The flow of hydrogen leaking backward from the rear of the vehicle shifts immediately upward because of its low density, then rises and gradually collides with pallets or other structures and diffuses. The leaking hydrogen is above the lower flammable limit in a range as high as the pallet, but afterward the concentration thins. The region of diluted hydrogen (0.3 volume %: gray) reaches the emissions louver about 480 sec (8 min) after the start of the leak. The hydrogen flowing out from the emissions louver is proportional to that leaking from the vehicle, and a steady state is reached in about 900 sec (15 min). The region above the lower flammable limit is restricted to a small area immediately behind the hydrogen leak, and to a height of about the distance to the pallet above.



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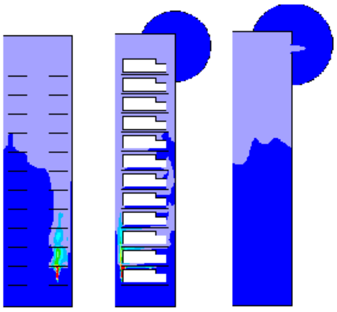
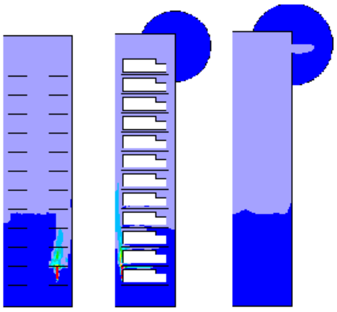


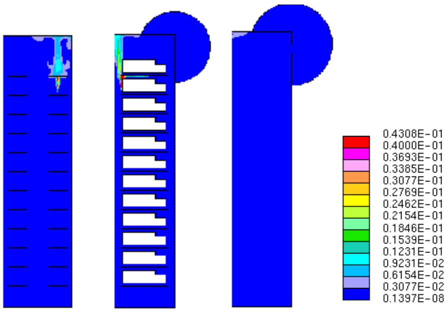
After 900 sec



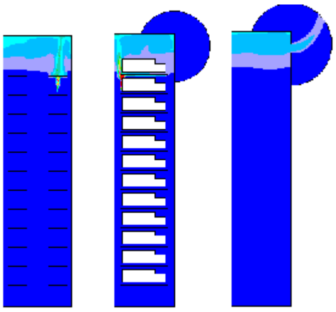
After 1420 sec

Figure 18. Hydrogen distribution in multistory parking garage (Case M-1; left: Section A, center: Section B, right: Section C).

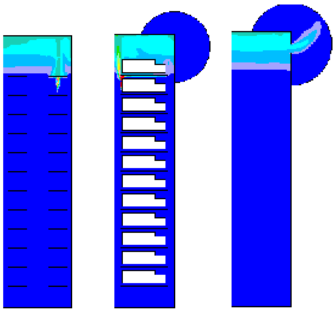
Secondly, the hydrogen concentration distribution in the case when the leak is from a vehicle on the second to highest level is shown in Fig. 19. The flow of hydrogen leaking backward from the rear of the vehicle is immediately deflected upward because of its low density. It rises and gradually collides with the pallet or other structure above and disperses. This is the same as in Case M-1. The region of diluted hydrogen (0.3 volume %: gray) reaches the emissions louver about 60 sec (1 min) after the start of the leak. The hydrogen flowing out from the emissions louver is proportional to that leaking from the vehicle, and a steady state is reached in about 600 sec (10 min). The region above the lower flammable limit is restricted as same as Case M-1.



After 20 sec



After 300 sec



After 600 sec

Figure 19. Hydrogen distribution in multistory parking garage (Case M-2; left: Section A; center, Section B, right, Section C).

Next, the changes with time in the hydrogen concentration at the upper edge of the emissions vent and at the center of the ceiling are shown for Case M-1 and Case M-2 in Fig. 20. The results show that when the hydrogen leak was from the lowest level the hydrogen concentration at the both the ceiling and emissions vent was below 1 %, and even when the leak was from the vehicle on the second to highest level the concentration was lower than 2 %.

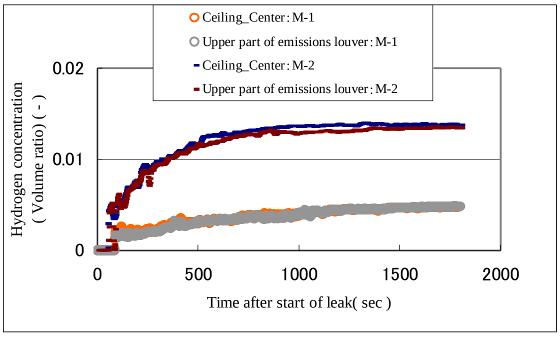
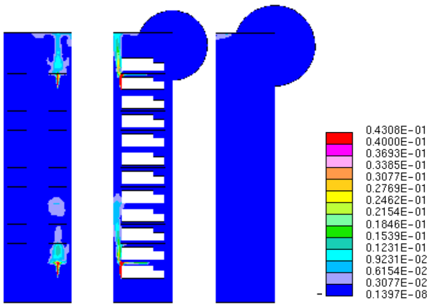


Figure 20. Changes with time in hydrogen concentration at ceiling and emissions vent in multistory parking garage (Cases M-1 and M-2)

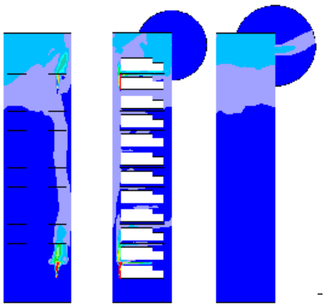
Influence of number of leaking vehicle

Figure 21 shows the hydrogen concentration distribution when there is a leak from both the vehicle on the second to top level and that on the bottom level (Case M-3). A small difference was seen in the diluted hydrogen concentration in the section above the highest vehicle pallet between Case M-3 and Case M-2. The diluted hydrogen in Case M-2 was stratified, whereas in Case M-3 the leak from the vehicle on the bottom level gave rise to slight turbulence owing to the gentle flow of dilute hydrogen within the parking garage. However, even in this case the region above the lower flammable limit was restricted to the space between the leaking vehicle and the pallet just above it.

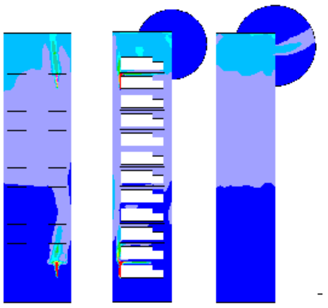
From the above, it thought that when predicting the diffusion of diluted hydrogen within a multistory parking garage, the hydrogen diffusion following a leak can be enough understood from a simulation of a hydrogen leak from 1 vehicle as a parameter of leak position.



After 20 sec



After 600 sec



After 1800 sec

Figure 21. Hydrogen distribution in multistory parking garage (Case M-3; left: Section A; center, Section B, right, Section C).

CONCLUSIONS

Continuous hydrogen leaks from 1 or 2 hydrogen fuel vehicles in large semi-enclosed spaces are not necessarily dangerous if they are at the allowable level for fuel leaks in collisions. This is because the hydrogen above the lower flammable limit is just one restricted area.

The phenomena on leaked hydrogen diffusion in each of the semi-enclosed spaces may be summarized as follows.

Tunnel

In a long tunnel with a rising and downing slope, hydrogen accumulates at below the lower flammable limit along the tunnel ceiling, but in an underwater tunnel there is no accumulation even at the tunnel ceiling. This is because the tunnel longitudinal slope rises toward the tunnel end, promoting the diffusion of hydrogen.

Underground Parking Lot

When air exchange occurs a regulated number of times, the leaked hydrogen is eliminated through the emissions vent. The hydrogen concentration flowing into the emissions vent is already below the lower flammable limit.

When there is no ventilation, hydrogen below the lower flammable limit spreads throughout the parking garage according to the shape of the ceiling.

Multistory Parking Garage

The leaked hydrogen soon diffuses to the pallet just above the vehicle at levels above the lower flammable limit, but afterward falls below the combustion limit.

When the leak is from the bottom level, diluted hydrogen below the lower flammable limit is filled in almost part of the parking garage.

Even when the leak is from the second to highest level, the hydrogen that accumulates at the ceiling is below the lower flammable limit. This is because parking garages are equipped with emissions vents at the top.

ACKNOWLEDGEMENT

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