ABSTRACT

| Title of Document: | AN ANALYSIS OF VEHICLE FIRES AND POTENTIAL METHODS TO REDUCE THEIR SEVERITY THROUGH MORE STRINGENT MATERIAL STANDARDS |

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In the United States, more than 1 in every 12 fire fatalities occurs in a passenger road vehicle; vehicle fires claim roughly 1200 injuries, $1.3 billion in property loss, and 490 lives annually. Very little progress has been made over the last several decades to confront the hazards of vehicle fires, but recently researchers and standards organizations have begun addressing these challenges. A literature review of the progress made and methods of reducing fire severity through technologies and standards was conducted. NFPA 556 is one proposed standard aimed at mitigating the hazards to occupants of vehicle fires; it was used to analyze the fire retardancy of a new, fire-resistant acoustic insulation material through small, bench, and large-scale testing. The feasibility of the use of this material in new vehicles for the reduction of losses was assessed through a cost-benefit analysis. Upon review of the results, it was determined that the new insulation did not pass all the requirements of NFPA 556. However, the standard does include stringent requirements, so the improved performance of the material should not be underappreciated. Based on the literature search and experiments, this standard, in combination with other fire protection technologies, provides a basis for improved vehicle fire safety.

AN ANALYSIS OF VEHICLE FIRES AND POTENTIAL METHODS TO REDUCE THEIR SEVERITY THROUGH MORE STRINGENT MATERIAL STANDARDS

By

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Chapter 1: Introduction

In the United States, more than 1 in every 12 fire fatalities, on average, occurs in passenger road vehicles [1]; these fires can develop and spread for a number of reasons, such as ruptured flammable or combustible liquid containers (fuel tank, fuel lines, engine oil, wiper fluid, etc), vehicle contents from occupants, and vehicle components (insulation, fabric, plastics) [1]. Depending upon the data used, these passenger vehicle fires claim between $700 million to $2 billion worth of property loss and nearly 500 human lives in a given year [1]. Occupant safety measures in the event of a collision have improved considerably over the last four decades, in large part due to the introduction of seatbelts, airbags, and crumple zones, but post-collision fire safety has not been addressed specifically during this period of time. Within the last decade, research into the vehicle fire problem has developed. Interest in the problem has increased, leading experts and researchers in the automotive industry and fire protection to begin tackling the vehicle fire problem through statistical and technological research.

Through the analysis of actual vehicle fires as well as large-scale tests, researchers have been able to identify critical issues with vehicles related to fires and their propagation. Two major issues have been identified through this research; pool fires under the vehicle and engine compartment fires represent the most detrimental of the fire scenarios. In this thesis, research will concentrate on the engine compartment fire scenario. Fire propagation through the firewall separating the engine and passenger compartments represents a critical area for improvement in vehicle fire safety based on data provided. Both heat transfer through this barrier as well as flame penetration are critical issues for

review and resolution; materials and methods to prevent both these penetration mechanisms are two of the many steps needed to reduce the severity of vehicle fires and their potential to harm occupants.

In most non-vehicle related fires, deaths usually occur due to toxic gas poisoning or asphyxiation from lack of oxygen, but because of the fast growth and the small volume of the passenger compartment, vehicle fire victims generally succumb to heat and flames first [2]. The speed of fire growth combined with extrication problems in the event of a collision provides a major objective for vehicle fire research. It is essential to delay flame and heat propagation into the passenger compartment for as long as possible to allow more time for extrication of victims.

Many research and development companies are beginning to address this issue with new technologies; they have based their designs on statistical data concerning fire origination, propagation, and severity from both field data and crash tests. These technologies range from active suppression systems, such as AFFF (aqueous film forming foam) or SPGG (solid propellant gas generators), to passive protection systems, such as powder panels or self-healing fuel lines [3]. Some of these have already been proven ineffective in the fight against vehicle fires, but some show great promise. In addition to the development of these technologies, there is a potential need for more stringent flammability standards that address the flammability hazards of the materials used in vehicles. With the increased usage of combustible plastics in motor vehicles, vehicle components represent a significant fire load. NFPA 556 is a 2007 draft document that addresses this issue. The

document is concerned with the reduction of fire hazards in motor vehicles through more stringent standards and a better understanding of how such standards would impact vehicle fire safety. It also critiques the current standards in use in the industry. The current flammability standard, FMVSS 302, has been criticized for its lack of assessment of critical properties for fire safety [1,4,5]. Many documents, including NFPA 556, confront this issue as well as others in an attempt to motivate improved vehicle fire safety.

It is important to stress that changing one or two materials in a vehicle will not drastically improve the fire safety of the vehicle. But as a whole, if enough materials are required to meet new, more stringent standards, then their cumulative effect would decrease the fire hazard to occupants. Product testing is an essential part of this process. One product that could stand to be updated through product testing is the acoustical insulation that is located in the footwells, dashboard, and trunks of passenger vehicles. This product serves dual roles as an acoustical and thermal insulator, though under current flammability standards, its heat and flame containment abilities are limited. Through various small, bench, and large-scale experiments, the fire performance of a new fire retardant acoustical insulation product has been evaluated and compared to the standards proposed by NFPA 556. These experiments focused on the acoustical insulation's role as a fire barrier in the firewall of vehicles. A portion of this report presents the experiments and their results, comparing the process and results to the proposed standards and research. Additionally, a cost-benefit analysis was conducted to determine the feasibility of adding this new fire retardant acoustic insulation to new vehicles.

The results of the analysis of the new fire retardant acoustical insulation are compared to the criteria stipulated by NFPA 556. The adherence of this new product to the new requirements set forth by NFPA 556 represents a first step in the improvement of vehicle fire protection. As researchers continue to develop and improve fire protection technologies and as NFPA 556 begins to regulate materials and components, a reduction in vehicle fire losses should follow.

The objectives of this thesis are to analyze current state of vehicle fire issues and research through a literature search and review and to subject a new acoustic insulation to the requirements of NFPA 556 and determine its viability in vehicle manufacture from experimental and cost-benefit results.

Chapter 2: Vehicle Fires

2.1 Vehicle Fire Issues

2.1.1 Impact of Vehicle Fires

In 2006, the NFPA reported that roughly 490 civilians died in vehicle fires. These 490 civilian deaths represent 13.7% of the total deaths associated with fire for 2006, including residential and non-residential structures. Also in 2006, vehicle fires accounted for $1.3 billion in property loss [6]. Additionally, there were 1200 civilian injuries reported [6]. These numbers indicate that, while survivability of automotive accidents has increased substantially in the last few decades due to advances in vehicle safety, vehicle fire safety is still a major concern. The numbers of deaths in accidents has decreased while the number of fire deaths in accidents has remained relatively constant. Until recently, little research was conducted concerning the problem of fire safety; in recent years, the U.S. motor vehicle industry has spent nearly $14 million per year researching the problem of motor vehicle fire safety [4].

This research by the U.S. motor vehicle industry has unveiled some major issues related to fires and their victims; the most compelling results are the statistical data concerning the topic. An analysis of vehicle fire data from 1994 to 1998 was conducted by NFPA 556. Table 2.1 shows fire losses for passenger road vehicles in the U.S.A. between the years of 1994 and 1998; it has been reproduced from the original table in NFPA 556, which contained fire losses from all vehicles (including air, rail, water, and road freight). Passenger road vehicles are all vehicles, which travel on public roads or highways.

Vehicle Type	Fires		Civilian Deaths		Civilian Injuries		Property Damage (Millions)	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Passenger Road Vehicle	295,170	73.80	330	56.20	1,403	59.80	$692.60	55.8

Table 2.1. Fire Losses in Passenger Road Vehicles in the U.S.A., 1994 - 1998 [1]

These percents in this table represent the percent of fires that occur in passenger road vehicles out of all vehicles (i.e. rail, water, and air). Passenger road vehicles represent 73.80% of the fires in all vehicles. These passenger road vehicles are broken down further in Table 2.2, also reproduced from NFPA 556. The table shows the percentage of automobiles (such as pickups, minivans, and sport utility vehicles) that contribute to the passenger road vehicle fire problem.

Vehicle Type	Fires		Civilian Deaths		Civilian Injuries		Property Damage (Millions)	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Automobile	280,550	95.00	302	91.60	1,161	82.80	$609.80	88.00

Table 2.2. U.S. Passenger Road Vehicle Fire by Vehicle Type, 1994 -1998 [1]

This data indicates that the "automobile" represents the majority of losses and casualties of all passenger road vehicles; automobiles represent 95% of passenger road vehicle fires and 70.11% of vehicle fires overall. At an average yearly value of $609.8 million dollars in financial losses and 300 deaths, automobile fires are a significant issue. To approach this issue in an attempt to reduce the severity and occurrence of vehicle fires, it is important to know why, where, and how vehicle fires happen as well as why and how victims die or sustain injuries as a result of fire.

2.1.2 Where Fires Originate and How They Propagate
Fires can originate in four major areas of a vehicle:

1) Engine compartment

2) Passenger compartment

3) Trunk or load-carrying area

4) Vicinity of vehicle [1]

Based on data gathered between 1994 and 1998, it was found that 67.3% of fires originated in the engine compartment, 17.2% originated in the passenger compartment, and 2.5% originated in the cargo trunk [1]. Ignition is caused by four major factors: part failure, leak or break (19.0%), short circuit or ground fault (18.3%), incendiary or suspicious (16.5%), and backfire (10.4%) [1]. These events tend to ignite two major materials which are liquid fuels (any flammable or combustible liquids in the vehicle) and electrical wire or cable insulation.

Fires in the passenger compartment represent the largest hazard to occupants, so even fires that start outside the passenger compartment are still a threat as propagation into the passenger compartment can occur. Fires in the vicinity of the vehicle, such as pool fires from gasoline, can quickly move into the passenger compartment. These pool fires usually result from rear collisions; from data, it has been found that if a vehicle involved in a fatal crash is struck in the rear, it is 140% and 340% more likely to have a fire as the most hazardous event, respectively, than a vehicle with damage to the front [7]. This is due to fuel tank rupture and the aggressive nature of the fire growth once ignited. Flames can enter the vehicle through split weld seams, gaps and holes in the floor pan, and any cracks in the frame or windows that may result from collision [8]. Fire spread from the trunk or cargo area occurs through wiring, vents, flammable upholstery, or stereo

components. Engine fires can result from mechanical or electrical failure or as a result of a collision [1]. As stated previously, 67.3% of fires originate in the engine compartment; if these fires are not controlled, they can propagate to the passenger compartment. The propagation of fire from the engine compartment is dependent on the size and numbers of openings in the bulkhead as well as the materials that are used to seal the openings in the bulkhead. Engine compartment fires therefore have the most potential for causing harm to occupants [1]. Prevention of this propagation mode of fire is the emphasis of this report.

Fires that start in the engine compartment can propagate to the passenger compartment in several ways. They can penetrate through the bulkhead, i.e. firewall, or through various openings such as HVAC, mechanical cables, wire harness, etc. Most of these openings are poorly protected from heat and flames or sealed with a combustible material, allowing penetration into the passenger compartment to occur readily. Other methods of propagation can occur as a result of flames traveling through the vents at the junction of the hood and the windshield; these flames, usually the result of burning flammable liquids from the engine, can cause the windshield to crack or melt, exposing the top of the dashboard area to flames [9]. In a General Motors study, flames propagated into the passenger compartment by means of holes in the windshield and through pass-through openings in the dashboard [9]. In the FM Global / MVFRI study, flames "entered the passenger compartment through windshield and dash panel openings", so a trend of flame propagation is apparent [8].

2.1.3 How Victims Die or Sustain Injuries

From tests conducted by various groups, the penetration of flames into the passenger compartment was found to be the most critical stage in terms of occupant safety. After flames and heat enter the passenger compartment, pain, 2nd and 3rd degree burns, flashover, toxicity and lethality follow in that order [2]. But the most critical aspect of a vehicle fire is heat. Because of the short time span in which heat will accumulate and flames will spread throughout the passenger compartment, the thermal hazard is more critical for the survivability of occupants than the toxic hazard [2]. In examinations of the carboxyhemoglobin (COHb) concentrations in the blood of victims of vehicle fire fatalities, it was found that the majority of fatalities had low concentrations of less than 10%; this indicates that these victims succumbed to the effects of heat or physical trauma before asphyxiation could occur [8]. There are still post-crash fires in which victims succumb to the toxic gases, but heat has been found to be the most deadly hazard.

Flame and heat propagation into the passenger compartment is a deadly occurrence. In nearly two thirds of vehicle fire deaths, the swift advance of fire and the ensuing incapacitation of passengers were contributing factors [10]. In full scale vehicle test burns, the engine compartments took between 10 to 25 minutes to reach full involvement [4,9]. Once the engine compartment was fully involved, flames spread into the passenger compartment in as little as one to six minutes, resulting in occupant death in 1 to 3 minutes due to the coinciding effects of heat, burns, and toxic gases [4]. Although this time span of up to 25 minutes seems more than adequate for occupants to extricate themselves or be extricated, there are several factors that must be taken into

consideration. In urban and rural areas, from crash time until rescue, Table 2.3 lists

rescue times.

Percentage of Crash Population	Time Until Care Received (min)	
	Urban	Rural
25%	5	9
50%	8	15
75%	12	24

Table 2.3. Crash time to rescue time of urban and rural areas [11]

Even in urban areas, 25% of the crash population may not receive emergency care for

more than 12 minutes. Meanwhile, in rural accidents, it could take more than half an

hour before an emergency response team arrives. In some cases, occupants may be

capable of extracting themselves from the vehicle; however, in other cases entrapment

could occur. Even if the vehicle is not deformed, the occupant may be too injured or

physically incapable of extricating themselves from the vehicle [11]. If this is the case,

these previously mentioned times until emergency care arrives begin to play a crucial role

in the survival of a vehicle fire victim. According to the Fatal Accident Reporting

System (FARS), the largest percentage of vehicle fires, 18.8%, occur during rush hour (3

p.m. to 6 p.m.) while the largest percentage of vehicle fire fatalities, 21.7%, occur

between the hours of 12 a.m. and 3 a.m. [12]. Once again, it is apparent that the fatalities

associated with vehicle fires are dependent upon the response time of emergency care or

civilian assistance.

The Motor Vehicle Fire Research Institute (MVFRI) has taken part in research

concerning vehicle fire safety with help from FM Global. A key part of this research has

been the statistical analysis of data on vehicle fires as gathered by the National Fire Incident Reporting System (NFIRS), the Fatality Analysis Reporting System (FARS), and the National Automotive Sampling System – General Estimates System (NASS/GES). They have found that from 2001 to 2003, there were more than 1200 fatalities associated with injuries sustained from fires. Of these 1200, approximately 28% required extrication, indicating that almost 120 occupants per year die due to their inability to extricate themselves from the vehicle [11].

Many victims survive post-crash fires. When post-crash vehicle fires do occur, approximately 83% of occupants in single vehicle accidents and 95% in multi-vehicle accidents survive without serious injury while 4.6% and 1.6% die, respectively; even the majority of occupants with severe injuries are able to escape, with 73.6% surviving in single vehicle accidents and 64% surviving in multi-vehicle accidents [8]. While these percentages of 4.6% and 1.6% are small, they still represent a large number of deaths. It is encouraging, though, that the percentages are so small because as Tewarson states, it is "…likely that even small improvements in decreasing the rate of fire hazard development in post-crash vehicle fires could lead to a reduction in injuries and deaths." [8]. This statement is validated by the proposal that if the passenger compartment can be made tenable for a longer period of time, then victims who require extrication may survive long enough for emergency services to arrive and control the situation. This further supports the theory that the longer a vehicle can sustain tenable conditions in the passenger compartment by suppressing fires [in the underbody, cargo trunk space, or engine compartment] before they spread or by impeding or slowing flame spread from the

engine compartment, the better chance the occupants have of surviving. Research into active fire suppression systems has been undertaken with varying degrees of success in extinguishment before flame spread. Additionally, passive protection systems are being studied for both flame propagation prevention and fire suppression.

2.2 Proposed Solutions to Vehicle Fire Problem

2.2.1 Research and Technology

The National Institute of Standards and Technology (NIST) has compiled a comprehensive document outlining the current technologies being researched, as well as those being proposed, concerning the issue of vehicle fires. The document, entitled "Vehicle Fire Suppression Needs", identifies the research needs associated with automotive fire protection [3]. This study has gathered documentation and studies from various entities working on a range of concepts to help reduce vehicle fires and the ensuing life and property loss.

A survey requesting information from approximately 300 companies offering technologies that could possibly improve the fire safety of vehicles was sent by J. Michael Bennett of NIST in 1998. Thirty-eight companies responded and a rudimentary analysis of the results was conducted in order to assess the "potential of the product to improve post-collision automotive fire safety" [3]. The ratings were based solely on engineering judgment without field testing or crash data. The systems that were evaluated included the active, passive, and fire resistant materials; a list of the technologies follows:

- Active fire suppression systems

  - Clean agents

  - Dry chemicals

  - Water mist

  - Aqueous film forming foam (AFFF)

  - Gas generators: pure gas and hybrids of clean agents and dry-chem

  - Pyrotechnic aerosol systems

  - Tubular fire extinguishing systems

  - Explosion suppression systems

- Passive fire protection systems

  - Self-sealing fluid lines

  - Enhanced fuel tank crashworthiness

  - Fluid shut-off devices

Of these systems, the highest ratings for fire safety potential were given to aerosol extinguishers, powder extinguishment systems, water mist systems, water based foam systems, and gas generator/hybrid systems for engine compartment fires. Additionally, all the passive fire protection systems were given high ratings.

2.2.1.1 Active Fire Suppression Systems

These active fire suppression systems all have successful track records outside of vehicle fire use. Handheld suppression devices as well as installed systems in structures have proven effectiveness and reliability. These systems could be assumed to be effective as

suppression systems in vehicles, but under realistic conditions with collisions, roll-overs, fuel spills, and dynamic ambient conditions results can and have been proven otherwise. The General Motors Corporation, which in 1995 agreed to spend over $51 million dollars to support research that would further vehicle safety ($10 million of which went to fire safety research) in conjunction with the US Department of Transportation [8], performed experiments with an uncrashed mid-size passenger vehicle and on-board fire suppression systems [3]. Fuel trails and environmental factors were considered during the experiments and results indicated that it was unlikely that an on-board fire suppression system would be able to completely extinguish all engine compartment and underbody fires; most of the suppressant types were found to be impractical for the application [3].

One potentially successful suppression system is in foams. A limited number of tests have been performed using foams such as AFFF, but the results from those tests are encouraging [3]. The use of foam in both engine compartment scenarios as well as underbody fires has potential as a small flame suppressant, but this system has yet to be proven in tests involving both collisions and fires. If high expansion foams are used, they can be used in rapid deployment to fill the underbody footprint of the vehicle in a thick, foam blanket. This blanket would cut off the fuel spill from ambient air supply, effectively removing the oxygen supply from a possible fire [3].

Full-scale underbody pool fire experiments by Hamins indicated that less than 300 grams of ABC and BC powder suppressants were effective at suppressing a gasoline pool fire directly under the vehicle. Once this pool fire was moved beyond the frame of the

vehicle, the suppressants were inadequate in the coverage and the fire continued burning [3]. Reignition is also a critical issue; even if a system is successful in extinguishing the initial fire, the hot materials, residual fuels, and ignition source (electrical spark) could still remain after extinguishment. If the suppression system has no secondary release, the fire hazard still remains. Even in tests where suppression systems adequately extinguish engine or underbody fires, such as those investigating the effective Solid Propellant Gas Generators (SPGG), experiments conducted by Santrock and Hodges show that dynamic factors [vehicle crush, winds, movement, and fuel reignition] can significantly reduce the effectiveness of an automatic fire suppression system [3]. A promising area of development for dealing with these dynamic factors is in hybrid SPGG's. A primary suppressant, the SPGG, would extinguish the initial fire and a secondary suppressant, a foam, would fill the area cutting off oxygen supply and preventing reignition.

Active suppression technologies other than gas or foam systems have been considered as well. In the event of a fuel spill under the body of the vehicle, non-flammable lightweight curtains would drop down from the frame of the vehicle, effectively cordoning off ensuing suppressant release and preventing air entrainment. Similarly, in the event of an engine compartment fire, a non-flammable insulation material attached to the hood would release and fall over the entire compartment; the fire would subsequently be smothered. These technologies have not been tested in full-scale, independent studies, so their effectiveness is not known [3].

2.2.1.2 Passive Fire Suppression and Prevention Systems

Passive fire suppression and prevention systems are inherently more reliable than active systems due to their independence of a detection device and simplistic nature. They are generally less expensive and require less upkeep than an active system and these qualities are attractive to both consumers and manufacturers.

A technology that is already in use in the aircraft industry and military is powder panels; these panels are made of molded thermoplastic, normally ribbed for rigidity, which contain a fire suppressant powder such as Monnex, KDKI, AL_2O_3 [and variants thereof], Purple K, potassium bicarbonate, and 10% acetate in water [13]. If a penetration into the panel is made, the agent contained within is released, thus inerting the space that has now become vulnerable to a fuel spill and fire. In the aircraft industry, these panels have been placed in aircraft dry bays for protection against ballistic impact and also have been considered for use in military land vehicles. The panels show considerable promise for issues related to fuel tank penetration in vehicles and considerable research is underway for improvement of these panels for more energetic release of agents, size to weight ratio, and longer powder suspension [3]. One area in which powder panels show a low probability of success is in engine compartment fires. Experiments by Hamins propose that due to the size of the engine compartment, the fire suppressant powder would need to be jettisoned to all corners of the compartment. Lining the entire engine compartment with powder panels would be uneconomical. One option already offered by a company is a thermally actuated powder panel that lines the hood and releases downward in the event of a fire [3].

Research conducted by the Next Generation Fire Suppression Program (NGP) into intumescent materials in aircraft has found that if strategically placed, the material will reduce the cross-sectional area of the engine enclosure in the event of a fire. As the material heats, it produces an "instant firewall", resulting in a smaller volume for a suppressant to be discharged. This firewall is not wholly reliable, though, due to the nature of intumescent materials; their expansion is not always complete, leaving areas for flame penetration [3].

In an FM Global / MVFRI study, researchers investigated the effectiveness of the application of fire retardant treatments of the HVAC units to block flame penetration through HVAC ducts and an intumescent painting of the underbody of the vehicle to block flame penetration through seams and openings in the floor pan. Results were discouraging as the fire retardant treatments of the polymer parts was ineffective in fire conditions normally found in a vehicle crash fire; the intumescent coating was ineffective as well. The study states that this could be due to the ineffectiveness of the type of coating and chemicals used, so these options should not be entirely discontinued [2].

Preventing post-collision fuel and fluid leaks from the engine and fuel tank does not completely mitigate the need for active fire suppression, but does reduce the dependency on it. As mentioned previously in Section 2.1.2, rear collisions result in a greater probability of a death occurring because of fuel tank rupture. If this fuel tank rupture can be prevented, than a pool fire will not occur and suppression is not required. Some

passive protection systems that have not been fully investigated but show promise are self-sealing fluid lines, enhances crash worthiness of fuel tanks, and fluid shut-off valves [3].

Finally, another important passive fire protection issue relates to the material used in the vehicle construction. Currently, many of the materials in vehicle interiors, dashboards, and pass-throughs are constructed of flammable polymers, plastics, and fabrics. The pool fires that result from molten polymer parts are major contributors to the fire intensity and flame propagation into the passenger compartment [2]. If these materials themselves are made more fire retardant with lower heat release rates and higher ignition temperatures, then the hazard of flame propagation and growth in the passenger compartment is reduced. This passive protection system may be the simplest way to reduce the fire hazard associated with vehicle fires; no additional space in the vehicle is needed for a suppression system and no alterations in the manufacturing process are added. The new product, with its improved capabilities, replaces the old product in the same installation process.

2.2.1.3 Active and Passive Systems Overview

During a Workshop on Fire Suppression Research Needs at the SAE World Congress in Detroit on April 13, 2005, several researchers and key individuals of the vehicle fire research problem discussed the strategies, technologies, procedures, best practices and R&D that could considerably improve fire suppression effectiveness in vehicles [3]. Their discussion is an excellent commentary on the current state of fire suppression

technologies; their major points provide an outline for the next steps to be taken to improve vehicle fire safety.

Regardless of the effectiveness of any fire suppression or prevention system, the most important aspect concerning its adoption into the automotive industry is cost. If a system is too expensive, then cost to benefit ratio may not be realistic enough for either consumers or manufacturers to accept the technology. Bennett emphasized that a well constructed market study should be undertaken to determine just how much the public and manufacturers are willing to pay for vehicle fire safety [3]. Because vehicle fire deaths are not a "mainstream" issue, at least relative to the stigma of collisions alone, the public's perception of the vehicle fire problem plays a large role in their acceptance of any costs to improve fire safety. Bennett relates the original difficulties that air bags met in their standardization process and that fire safety technologies could meet the same initial opposition. But if the statistics are provided to show that the investment in these technologies is proportional to lives and property saved, progress could be made [3].

There is a generous amount of research and development taking place concerning the vehicle fire problem. Many of these systems have been tested in the full-scale environment and show promising results. More research remains to establish the crashworthiness and placement strategies of fire suppression hardware. In a vehicle fire that originates in non-collision incident, these suppression systems may be highly effective, but in event of a collision or roll-over, these systems may become compromised. Tewarson of FM Global confronted this issue by stating that

considerations of both active and passive fire mitigation systems should be made [3]. If a complicated active suppression system becomes inoperable in the event of an accident, the redundant passive protection system should still protect occupants. The passive system approach is needed to prevent flame and heat spread into the passenger compartment [3].

Gann of NIST suggested the substitution or modification of flammable vehicle fluids and thermoplastic materials should be taken into account. He posed the question of just how many lives could be saved by if underhood fluids were less flammable or if "flammable materials were substituted with materials with appreciably improved fire resistant behavior." [3]. Any measures taken that restrict the rate at which a material releases heat can be expected to slow fire growth in most circumstances [1].

The implementation of an effective, lightweight and inexpensive on-board fire suppression system in conjunction with passive protection systems would be a substantial step in the reduction of fire fatalities, injuries, and property losses [3]. The current standards used to rate the components of motor vehicles in terms of fire safety do not provide stringent enough regulations on the materials; thus, improvements in the materials used in motor vehicles are unlikely to occur until these standards are improved as well. The only current existing requirements related to fuel and material flammability are the Federal Motor Vehicle Safety Standard (FMVSS) 301 Fuel Integrity Test and 302 Flammability of Interior Materials, respectively [3]. This report concentrates on the limitations of FMVSS 302 because of its relation to flame propagation from the engine

compartment to the passenger compartment and as such FMVSS 301 will not be discussed further. Many entities have addressed the limitations of FMVSS 302, with the National Fire Protection Association leading the movement toward a better flammability standard.

2.2.2 Current Standards and Changes to Be Made

A new draft document of NFPA 556, addresses FMVSS 302 and its limited applicability to the current materials used in vehicles. The proposal is entitled, "Guide for Identification and Development of Mitigation Strategies for Fire Hazard to Occupants of Passenger Road Vehicles" and is concerned with the following issues: ignition, fire performance characteristics of materials, ventilation factors, and heat and smoke release of the materials and assemblies, inside and outside the vehicle, that have an effect on fire hazard to the vehicle occupants [1]. It proposes that the current standards used, such as the Federal Motor Vehicle Safety Standard 302 (FMVSS 302), to monitor the materials used in the automotive industry are not strict enough [1].

FMVSS 302 is considered specifically due to its use as a standard for flammability of materials of construction. At its inception in 1972, the standard was established as a method of reducing deaths and injuries to occupants of motor vehicles by way of a standard of flammability [4]. It was estimated that 30% to 40% of vehicle fires originated in the passenger compartment, normally as a result from cigarette or match ignition of the vehicle's interior or trunk [4,14]. Since then, vehicles and their manufacture and occupants have changed significantly. According to the NASS, less

than 10% of vehicle fires now originate in the interior of vehicle; this statistical reduction can be accounted for by improved impact-survivability during crashes, stronger and better protected fuel tanks, and compartmentalization of vehicles. Unfortunately, even with this reduction in the amount of vehicle fires of interior origin, when exterior fires propagate inward the results can still be fatal.

Since 1960, the average amount of combustible materials present in vehicles has increased from 9 kg [15] to 90 kg as of 1996 [1,16]. Currently, combustible plastics represent the main fire load in a standard vehicle. While not only being the first material to ignite in a vehicle fire in most circumstances [17], plastics have high heat release rates and high levels of toxic gas output, greatly increasing the fire hazard for passengers. Plastics used in vehicles consist of polyurethane, polypropylene, polyvinyl chloride, polyethylene, polyamide, acrylonitrile butadiene styrene, sheet molded composites and bulk molded composites, polycarbonate, polyethylene terephthalate, polybutylene terephthalate, polystyrene, polyphenylene oxide, styrene maleic anhydride, and various other polymers and epoxy resins [1].

Additionally, plastics can ignite and spread flames like solids, but may also drip and pool like liquids; this represents an aspect that needs to be considered by a flammability standard. Other fire performance properties that a standard should take into account include heat release, smoke production, ignitibility, flaming drips, and the effects of orientation of vehicle components [1]. FMVSS 302 does not take any of these factors into account, thus reinforcing NFPA 556 suggestion for its modification or removal [18].

Although these properties would be difficult to observe through one test alone, a major concern is heat release rate. Measures taken to restrict heat release rate would significantly reduce the effects of a burning material.

In addition to NFPA 556, multiple other research endeavors and technical studies indicate that FMVSS 302 is an aging standard that has little potency in current automobile manufacturing. In 1979, only seven years after its inception, the National Materials Advisory Board (NMAB) stated the following concerning FMVSS 302:

> (1) "This standard prescribes a test method that tests materials only in a horizontal orientation and is considered by test experts to be totally ineffective in providing fire safety in a real fire situation."
>
> (2) "Although all these materials are required to pass FMVSS 302 with a horizontal burning rate not exceeding 4 in. per minute, most of them are used in a vertical configuration where the actual burning state would be expected to be several times that exhibited in the horizontal configuration."

Nearly thirty years after these statements were made, FMVSS 302 is still in use and remains one of the only fire tests normally used in transportation.

As mentioned previously, since the standard's introduction nearly 40 years ago, vehicle attributes and collision properties have changed significantly. Concerns that were paramount in the first few decades of the standard's use are no longer as significant due to improved vehicle collision safety, reducing the standard's applicability. On the other hand, the increased use of combustible materials such as plastics and composites has

outgrown the standard by altering the fire scenarios currently possible [18]. FMVSS 302 is not a rigorous test and when dealing with the large quantity of plastics and composites in today's automobiles, it only serves as a screen for the more flammable materials used [4].

According to an article, not even one-third of the almost 20 m^2 of combustible fabrics, plastics, and foam surfaces found in today's vehicles are represented by FMVSS 302 [5]. This is not to say that the remaining two-thirds do not pass the standard but that once they are installed, they are no longer in the horizontal, upward facing position [the position tested in FMVSS 302], one of the concerns expressed by the NMAB [5]. Flame spread in the vertical orientation is much faster than in the horizontal direction. This can be attributed to the fact that the flames in the upward orientation are gravity assisted by the convective flow, buoyancy effects, and ignition of contiguous surfaces by flaming drops of material [4]. Because of the combination of thermal diffusion and convective flow, more and more of the material becomes exposed to the thermal insult in the vertical orientation. This leads to a flame spread rate drastically different than that found in the horizontal orientation. By changing the orientation of the material by ninety degrees, the FMVSS 302 standard loses its validity. The authors of the scholarly article "Improving Survivability in Motor Vehicle Fires" working with the Motor Vehicle Fire Research Institute (MVFRI) state their concerns with FMVSS 302:

> "…FMVSS 302 is no longer relevant to automobile fire safety and recommend
> improved standards based on objective criteria for fire safety performance

(fireworthiness) at the system/vehicle level as is routinely done for

crashworthiness." [4]

One concern of researchers and automobile manufacturers is the expansive use of

FMVSS 302 by the international automotive community. It has many corresponding

tests that practically mirror the standard's test procedure; these include the following but

are not limited to: ISO 3795, BS AU 169, and SAE J369 [4]. Any country that has a

substantial automotive industry utilizes some form of FMVSS 302 [18]. Thus, a

particularly thorough and adoptable new standard must be introduced for dissemination

into the international automotive industry.

The editors of NFPA 556 hope that this proposed standard will step into this

responsibility. For each area of fire origination, NFPA 556 lays out guidelines for the

materials used in those particular areas. For the barrier between the engine compartment

and passenger compartment, both NFPA 556 and the MVFRI study recommend the use

of materials that can separate the two compartments and act as a barrier preventing the

passage of flames and hot gases for no less than 15 minutes to 20 minutes when exposed

to the fire exposure curve in ASTM E 1529, maintaining survivable conditions in the

passenger compartment [1,4]. NFPA 556 also stipulates that materials used in the

ductwork should have times to ignition no lower than 90 seconds when tested at an

incident heat flux of 25 kW/m^2 in the cone calorimeter in the horizontal position [1].

Their average heat release rate must be no more than 80 kW/m^2, from ignition to the

completion of three minutes, when tested in a cone calorimeter in the horizontal

orientation at an incident heat flux of 25 kW/m^2 [1]. The MVFRI study suggests a heat release rate maximum of 100 kW/m^2, which it correlates to the fire performance of aircraft cabin materials and self-extinguishing plastics [4]. The materials must also not produce flaming drips when exposed to heat and flame [1]. Lastly, by fire-hardening bulkheads, openings, and conduits between the engine and passenger compartments through fire resistive materials or intumescent seals, fire penetration will be delayed [4].

A major hurdle in vehicle fire protection that NFPA 556 has attempted to overcome is the concept that one, single technology is required to solve the fire problem. Vehicles are complicated machines with many areas for component failures, so relying on one technology to prevent deaths, injuries and property loss is not effective. No one addition to a vehicle will eliminate the fire problem, but the collective effect of small changes throughout the vehicle and its components will add up and greatly increase the fire safety of automobiles. NFPA's new proposal endeavors to make these improvements through a more stringent and encompassing standard in the form of NFPA 556.

NFPA 556 proposes general guidance for testing to assess improved fire performance of materials or products. Full-scale (large-scale) fire tests are excellent ways to assess heat release properties and are the most representative way to find where the deficiencies in fire safety lay in a vehicle. These full-scale tests are expensive and difficult to conduct, however, they are a limited method of testing. Medium-scale tests allow results similar to full-scale, but without the high cost and difficulty. They provide results from fuel packages and a means of understanding the interactions between materials. Bench-scale

tests using the cone calorimeter can provide much needed heat release, ignition, and mass loss data essential for selecting materials based on given constraints. Finally, the small-scale tests such as FMVSS 302 that test for particular fire properties are a useful addition to the other tests as long as they themselves are not used solely for material decisions [1].

2.2.3 Product Testing

The product tested specifically in this report's research is the acoustical insulation that is located in the firewall and trunk of vehicles, but the experiments and considerations focused solely on its use in the footwell. In its use in the firewall, it is located under the footwell carpeting and depending upon the vehicle make and model, sometimes extends into the area behind the dashboard. It is a non-woven fabric that is compressible and approximately one inch thick.

This product serves dual purposes as an acoustical and thermal insulator; under current standards, its heat and flame containment abilities are limited. As fires propagate from the engine compartment into the passenger compartment, the insulation should help to insulate the dashboard and passenger compartment from heat transfer; unfortunately, due to the limited insulative qualities and propensity to flame spread, this insulation does not meet its potential in protecting occupants from fire hazard. If the material were to meet the new standards of NFPA 556, it would improve the protective ability of the insulation.

New methods of fire retardancy application have improved the fire protective capabilities of acoustic insulation. Rather than merely coating the material with a fire retardant

liquid, the material is forced to absorb the retardant throughout its volume, increasing it

fire resistant qualities. Figure 2.1 shows a side view of the FR Material insulation.

Figure 2.1. FR Material side view

Through various small, bench, and large-scale experiments, the validity of this product

has been evaluated and compared to the standards proposed by NFPA 556. In addition, a

cost-benefit analysis has also been conducted to evaluate the feasibility of introducing the

product into use in the automotive industry based on its performance in experiments.

Chapter 3: Methodology

3.1 Introduction

To increase the survivability of the passenger compartment from engine compartment fires, the fortification of the firewall is essential. There are two main qualities that are essential for the performance of the firewall:

1) Materials that prevent the spread of flames and hot gases

2) Materials that do not add significant amounts of heat or smoke to an already involved fire

The material examined in this study was a non woven acoustic insulation is used in an assortment of areas throughout the vehicle, from the firewall to the headliner to the trunk. Although the insulation currently used by the automotive industry passes FMVSS 302, it does not pass the standards set forth by NFPA 556. The new insulation, referred to as FR Material, along with the current insulation, referred to as Current Material, were run through a range of tests. These included the following:

1) Small-scale

   a. Horizontal FMVSS 302 test

   b. Vertical flame spread test

2) Bench-scale: cone calorimeter tests

3) Large-scale: full sized vehicle test burns

In addition to the experimental tests, a cost-benefit analysis was performed in order to evaluate the replacement of the currently utilized acoustic insulation with the FR Material insulation.

3.2 Experimental Methodology

3.2.1 Small-scale Tests

Small-scale tests were performed at the University of Maryland College Park. Both horizontal and vertical tests were performed. The horizontal tests were similar to FMVSS 302 as stipulated in the NHTSA Laboratory Test Procedure for FMVSS 302 [19]. Both insulation types, FR Material and Current Material, were cut into 102 mm by 356 mm strips and laid on two thin rods, to support the fabric, in a burn test cabinet. Ignition was caused by a methane Bunsen burner with a flame height of approximately 38 mm placed under the sample (edge of the burner top was 19 mm from the sample). The FMVSS-302 standard requires that the material burn at a rate of no more than 102 mm per minute or stop burning before 60 seconds and has not burned more than 51 mm, so results were gauged on these requirements.

The vertical test was performed with samples cut from each insulation of the same size as the horizontal test. The burn test cabinet was placed in the vertical position and the samples secured one at a time in the cabinet. Once again, the methane burner with a flame of 38 mm was placed under the sample with the burner top 19 mm from the sample for ignition. The same requirements to be met during the horizontal FMVSS 302 test could not be used in the vertical test because of the rapid nature of vertical flame spread; a subjective approach was used to compare horizontal flame spread to vertical flame spread and illustrate why FMVSS 302 does not correlate to vertical orientations.

3.2.2 Bench-scale Tests

Bench scale tests were conducted using a cone calorimeter. The purpose of these tests was to obtain ignition parameters at various incident heat fluxes, heat release rate values for the samples at various incident heat fluxes, and interface temperatures between the sample and a steel backing plate. Incident heat fluxes of 15, 25, and 50 kW were used; three tests for each material at each heat flux were conducted for a total of 18 tests. The test setup involved 10 by 10 cm samples of the insulation material placed above a 0.32 cm thick steel plate with a thermocouple mounted at the interface between the two materials to obtain the interface temperature as a function of time (this setup simulates the insulation's use in the real-world situation). This arrangement was then placed in the sample holder and prepared for insertion into the Cone Calorimeter. Test specimens were mounted horizontally in the Cone Calorimeter with a protective cover in place to prevent exposure to the incident heat flux before timing and data collection began. Timing and data collection were initiated upon the removal of the protective cover. If the sample ignited and flame extinction subsequently occurred, after 15 seconds the electric igniter was reintroduced above the sample for 10 seconds in an attempt to reignite the material. If ignition occurred, the specimen was allowed to burn until it self-extinguished; the time to burnout would be recorded and the process would be repeated until the sample would no longer ignite. Data recorded involved the following:

- Time to ignition (as well as subsequent ignitions as they occurred)

- Time to burnout (as well as subsequent burnouts as they occurred)

- Heat Release Rate

- Mass loss

- O$_2$ percentage

- Gas temperature and interface temperature

- Video documentation

3.2.3 Large-scale Tests

The large-scale insulation test burns were completed at the Maryland Fire and Rescue

Institute (MFRI) in College Park, MD. Two vehicles provided by MFRI were used in the

test burns. One vehicle was an early 1990's Dodge Neon (small four door sedan) and the

other was a 1990's Infiniti J30 (mid-size four door sedan). As shown in Figure 3.1, the

two vehicles were positioned facing each other raised on concrete cinder blocks.


Figure 3.1. Vehicle orientation

Two sheets of gypsum wallboard were placed under each vehicle to help prevent spalling

of the concrete pad; a drainage ring surrounded the concrete pad to contain water runoff

during the extinguishment of the fire. The front tires of the vehicles were deflated to

reduce any hazard associated with their bursting.

Both vehicles were stripped of their factory-installed firewall insulation; this insulation was replaced with the baseline insulation, Current Material, and fire resistant insulation, FR Material, in the Dodge and Infiniti, respectively. Both vehicles had a limited amount of firewall insulation in the foot well and behind the dashboard. Each vehicle was instrumented with eight (8) 20-gauge Type K thermocouples located as follows (for each set, one thermocouple was placed on each side):

- Two (2) on the right and left sides of the engine compartment within a foot of the firewall at approximately the level of occupant feet;

- Two (2) just above the dashboard several inches from the windshield along the centerline of the front driver and passenger's bodies;

- Two (2) in the foot wells of the front driver and passenger seats; these thermocouples were placed between the carpeting and the firewall insulation

- Two (2) in the front driver and passenger's seats at waist level

*See Figure 3.2 for a diagram of these locations
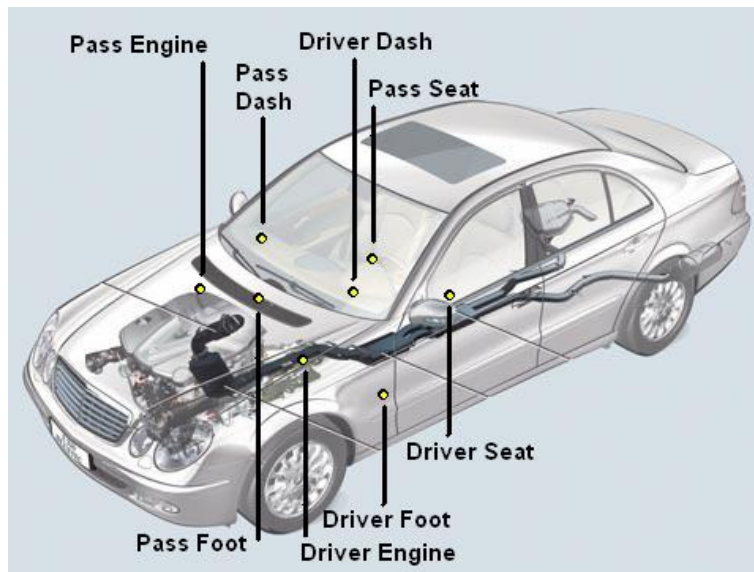
Figure 3.2. Diagram of thermocouple locations

A pan of heptane has been used in previous experiments to initiate vehicle engine fires, but due to stricter EPA standards imposed on MFRI recently, only Class A materials may be used. Trained MFRI personnel loaded the engine compartments of the vehicles with Excelsior (shredded wood material) as the initial fuel load. The Excelsior was placed both above and below the engine to ensure proper ignition.

The Excelsior was ignited with a road flare in several areas of the bundle. Time-temperature data was monitored and recorded using a Data Acquisition System connected to a laptop computer. Video and photographic documentation took place throughout the tests. The burns were allowed to continue until noticeable impingement of flames and heat damage occurred in the passenger compartment of the car.

3.3 Cost-Benefit Analysis Methodology

3.3.1 Purpose of Project

A cost-benefit analysis following the methods used by the California Department of Transportation was conducted to determine the cost effectiveness of replacing the acoustic insulation currently in use by automotive manufacturers with FR Material's new insulation [20]. The product's purpose is to prevent or slow the propagation of fire and heat into the passenger compartment of a vehicle in the event of a fire. This would hopefully prevent a certain percentage of injuries and deaths as well as property damage.

3.3.2 Project Description

A new fire retardant acoustical insulation will be installed in new automobiles as a replacement to the insulation currently being used by automotive manufacturing plants

throughout the US; in this cost-benefit analysis, vehicles sold in the US are only considered. The material would be put into use as soon as the infrastructure (purchase and shipment) allowed, most likely within the next two years. The new insulation would be used in place of the current insulation, requiring no additional training or alteration of assembly practices.

3.3.3 Purpose of Analysis

This analysis will provide results to help determine whether the insulation should in fact be replaced. This will be determined by considering if the benefits of replacing the insulation [lives saved, injuries reduced, property damage costs reduced] outweigh the costs [variable from $5 to $10]. The costs of replacing the insulation would be felt by the manufacturers and then carried to consumers. The base case is that no changes are made and the insulation is not replaced with FR Material's product. Current trends of property loss and casualties continue. The cost-benefit analysis spanned a period of ten years, starting with the year of initial installation to ten years beyond.

3.3.4 Type of Benefit-Cost Analysis

A parametric analysis was conducted using a net present value method. In this method, the total discounted costs are set equal to the total discounted benefits and by altering a particular variable, a maximum cost effective value can be found for that variable. The calculation is made as follows:

n: number of years

B_i: benefits of project in year i

C_i: costs of project in year i

d: discount rate

1st Step: discount the costs and benefits in future years

$$i = B_i \big/ (1+d)^i$$
$$i = C_i \big/ (1+d)^i$$

2nd Step: sum discounted benefits and discounted costs and set equal to each other to determine baseline effectiveness

$$\sum B_i \big/ (1+d)^i = \sum C_i \big/ (1+d)^i$$

3.2.5 Calculation Justification

To determine the benefits of the safer cars, it was necessary to determine the percentage of cars on the road that have the new insulation installed; for each year, the number of cars produced in that year (assuming they all have the new insulation installed) was divided by the total number of registered vehicles. For each following year, the number of cars produced was added onto the number from the previous year. To determine the number of deaths, the number of deaths per year was multiplied by the percentage of safer cars on the road. This result would be the amount of deaths that could be associated with the safer cars.

In the parametric analysis, the installed cost was varied to determine how many lives and property would need to be saved so that the benefits were equal to the costs; because injuries only represent 2.1% of the total monetary impact of vehicle fires, they were deemed negligible and were not considered in this analysis. According to the Environmental Protection Agency, the value of one human life is $3.7 million or if one is 70 years of age or older, $2.3 million [21]. According to the US Department of Transportation Federal Highway Administration's Highway Statistics for 2006, there are

a total of 202,810,438 licensed drivers in the US; 20,588,891 of these drivers are over the age of 70 and represent 10.15% of the licensed drivers [22]. This percentage was estimated to be the total number of individuals over 70 on the road as well. Using this percentage, the value for human life of $3.55 million was calculated, where 89.85% of individuals on the road are valued at $3.7 million and 10.15% are valued at $2.3 million. According to the NFPA, property loss due to vehicle fires is estimated at $1.3 billion per year. To determine the total benefits met by installing the FR Material product, the cost of life saved and property saved were summed. To determine the expense of installing FR Material, the installed cost per car ($5 to $10) was multiplied by the number of cars produced per year. Then these values were placed in the equations from Section 3.2.5 and the results were analyzed.

3.2.6 Values and Calculations
Percentages

To calculate the number of safer cars manufactured per year, data concerning the number of vehicles registered annually in the US was collected from the US Department of Transportation [22]. Annually, there are roughly 7,667,066 new vehicles registered in the US; this value is kept constant over the span of the analysis as it has been assumed that vehicle production rate is relatively stable by the year 2008. The value was multiplied by the year of the study to calculate compounding years as shown in equation 3.1.

$$n_{FR} = 7,667,066i \quad (3.1)$$

In this equation, i is the number of years passed (with the yearsused in the study ranging from 1-10) in the analysis and n_{FR} is the number of safer cars on the road in year i. The percentage of vehicles on the road that have the FR Material installed was then

determined by dividing n_{FR} by the number of registered vehicles in the US as shown in equation 3.2. This value was obtained from the US Department of Transportation and is roughly 237,000,000 [22].

$$\%_{FR} = \frac{n_{FR}}{237,000,000} \quad (3.2)$$

Now, $\%_{FR}$ represents the percentage of cars on the road in a particular year that have the FR Material installed. From this percentage, the number of deaths associated with vehicles containing FR Material was calculated using a total number of deaths of 490 from the NFPA as shown in equation 3.3.

$$n_{deaths,FR} = (490 \text{ deaths}) \cdot (\%_{FR}) \quad (3.3)$$

Now, $n_{deaths,FR}$ represents the number of deaths associated with vehicles on the road that have FR Material installed. These are the number of lives that could potentially be saved by the FR Material.

Benefits and Costs

To find the benefits due to deaths saved by vehicles with FR Material installed, n_{lives} was multiplied by the cost of human life, again $3.55 million, and a variable reduction percentage. The formula used is shown in equation 3.4.

$$B_{death} = (n_{lives}) \cdot (\$3.55 \cdot 10^{6}) \cdot (\%_{deaths\ reduced}) \quad (3.4)$$

To find the benefits due to property loss saved by FR Material installed vehicles, $\%_{FR}$ was multiplied by the total cost of property loss, $3.1 billion, and a variable reduction percentage. The formula is shown in equation 3.5.

$$B_{property} = \left(\%_{FR}\right) \cdot \left(\$1.3 \cdot 10^9\right) \cdot \left(\%_{property\ saved}\right) \quad (3.5)$$

To calculate the installed cost of FR Material insulation, the number of cars manufactured each year [7,667,066] was multiplied by the cost of insulation, which was varied from $5 to $10 in one dollar increments. This formula is shown in equation 3.6.

$$C = 7,667,066 \cdot C_{install}$$

Once the benefits and costs were calculated, the discounted benefits and costs were calculated to take into account the time-value of money over the ten year span of the analysis. The formulas for discounted benefits and costs in future years are shown in equations 3.7 and 3.8, respectively.

$$B_{discounted} = B_i \big/ \left(1 + 0.03\right)^i \quad (3.7)$$

$$C_{discounted} = C_i \big/ \left(1 + 0.03\right)^i \quad (3.8)$$

Where 0.03 is the discount rate as found from the Consumer-Price Index [23]. These discounted benefits and costs were then summed over the span of the analysis and set equal to one another to determine the "break-even" reduction percentages of deaths and property loss; this formula can be seen in equation 3.9.

$$\sum B_i \big/ \left(1 + 0.03\right)^i = \sum C_i \big/ \left(1 + 0.03\right)^i \quad (3.9)$$

The variable percentage reduction necessary to "break-even" between cost and benefit was found through trial and error until the accurate percentages were calculated.

Chapter 4: Results and Discussion

4.1 Introduction

The experimental results from the small, bench, and large-scale tests will be presented

first, followed by the results from the cost-benefit analysis. A discussion of impact of the

results will follow.

4.2 Experimental Results
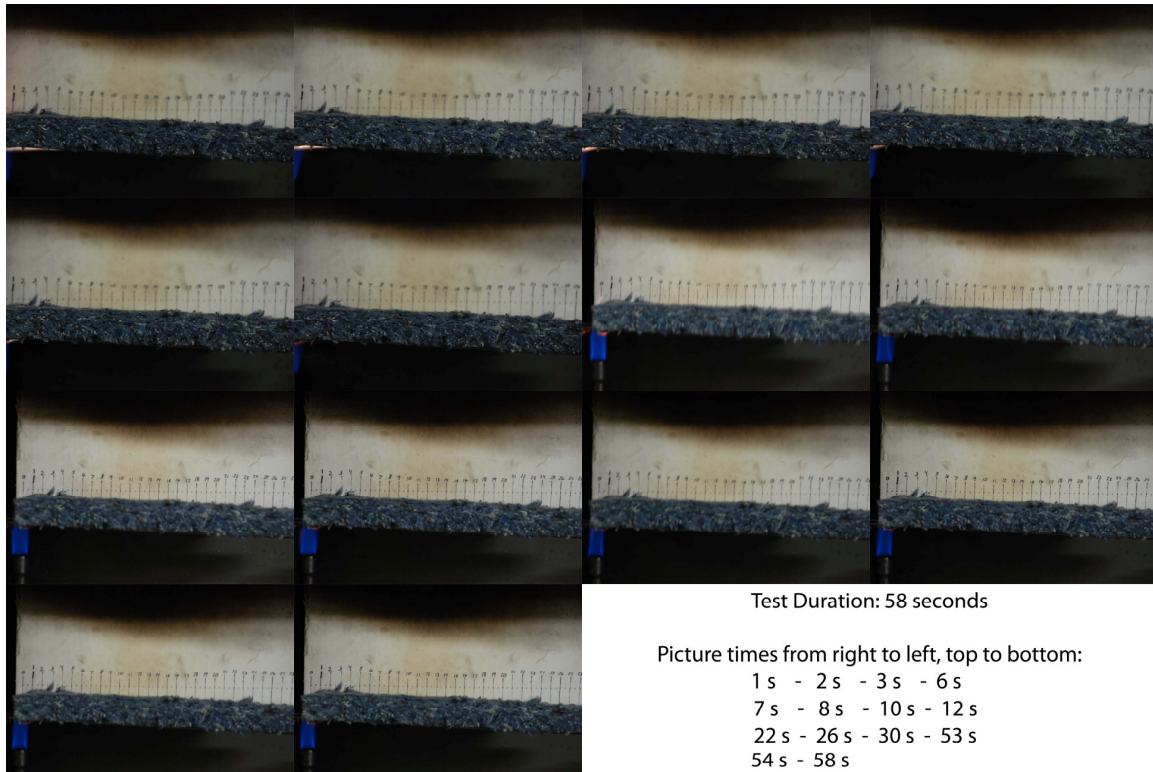
4.2.1 Small-scale Tests

In the small-scale tests, tests similar to the FMVSS 302 and a modified vertical test were

performed. These tests aimed to illustrate flame spread in both the horizontal and vertical

positions for the two insulation samples. There were differences in the results between

the two samples, both in the vertical and horizontal orientations.

4.2.1.1 Horizontal Flame Spread Test Results

These tests were conducted in the horizontal orientation as indicated by the FMVSS 302

standard.

- **FR Material**

Negligible flame spread occurred along the length of the insulation for the duration of the

test. Figure 4.1 shows time lapse photographs of the FR Material test.

Test Duration: 58 seconds

Picture times from right to left, top to bottom:
1 s - 2 s - 3 s - 6 s
7 s - 8 s - 10 s - 12 s
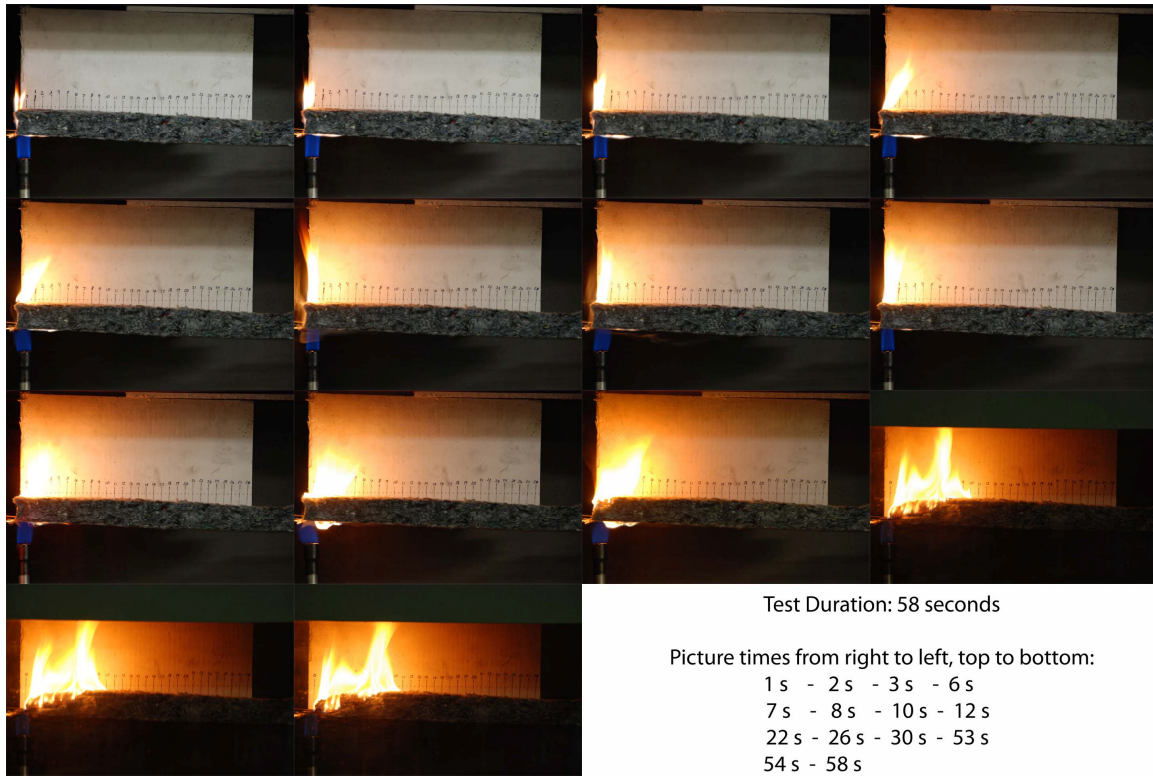22 s - 26 s - 30 s - 53 s
54 s - 58 s

Figure 4.1. Photographs of FR Material horizontal flame spread test

Each line on the white background along the length of the sample in the photographs is 1

cm. In the lower right corner of the figure, the total test duration and time elapsed for

each picture [moving left to right and top to bottom] is listed. As shown, no flame spread

occurred for the duration of the test, resulting in an approximate flame spread velocity of

at most 5 mm/s.

- **Current Material**

The Current Material showed flame spread that was faster than the FR Material. Figure

4.2 contains time lapse photographs of the Current Material test.

Test Duration: 58 seconds

Picture times from right to left, top to bottom:
1 s - 2 s - 3 s - 6 s
7 s - 8 s - 10 s - 12 s
22 s - 26 s - 30 s - 53 s
54 s - 58 s

Figure 4.2. Photographs of Current Material horizontal flame spread test

Each line on the white background along the length of the sample in the photographs is 1 cm. In the bottom right corner of the figure, the total test duration and time elapsed for each picture [moving left to right and top to bottom] is listed. As shown, flame spread was minimal in the first 12 seconds of the test, with significant flame spread occurring at 26 s and beyond. By the end of the test at 58 seconds, flames had spread more than the maximum distance of 102 mm allowed by the FMVSS 302 standard. Figure 4.3 is a larger image of the last photograph in the progression allowing a better view of the distance propagated by the flames.

Figure 4.3. Flame spread at 58 s into Current Material test

The FMVSS 302 standard states that flames must not spread with a velocity more than

102 mm per minute [1.7 mm/s]; in the Current Material test, by 58 seconds the flames

had spread 110 mm, resulting in a flame spread velocity of 1.89 mm/s. This value is

greater than the accepted maximum by the standard, but these tests are not official

FMVSS 302 test set-ups so judgments in terms of FMVSS 302 cannot be made.

Although the horizontal test was similar to FMVSS 302, the standard was not completely

used to design this test set-up.

4.2.1.2 Vertical Flame Spread Test Results
No particular flame spread velocity was used as a gauging factor for failure because of

the difficulty in measuring vertical flame spread [see discussion in Section 2.2.2].

Instead, the test was used as a comparison between the resistances to flame spread in the vertical orientation of the two samples.

If it is taken into consideration that this material is found in the vertical orientation when installed in vehicles, these tests play an important role in determining the reliability of each material as a fire-safe additive as well as conveying the limitations of FMVSS 302.

- **FR Material**

The FR Material sample was retardant to the spread of flame in the vertical direction. Charring could be seen on the portions of the sample upon which the flame, or sometimes the very beginning of the hot plume, impinged, but beyond the flame no visible damage occurred. The material was resistant to flame spread, even in the vertical orientation. These results are shown in the photographs in Figure 4.4.
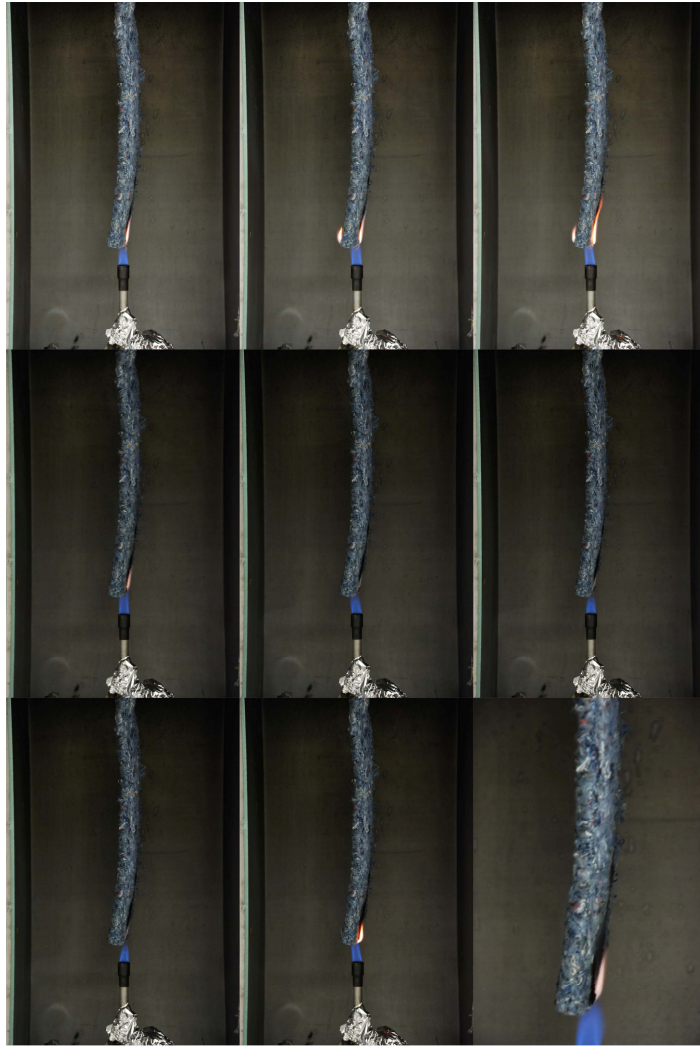
Test Duration: 71 seconds

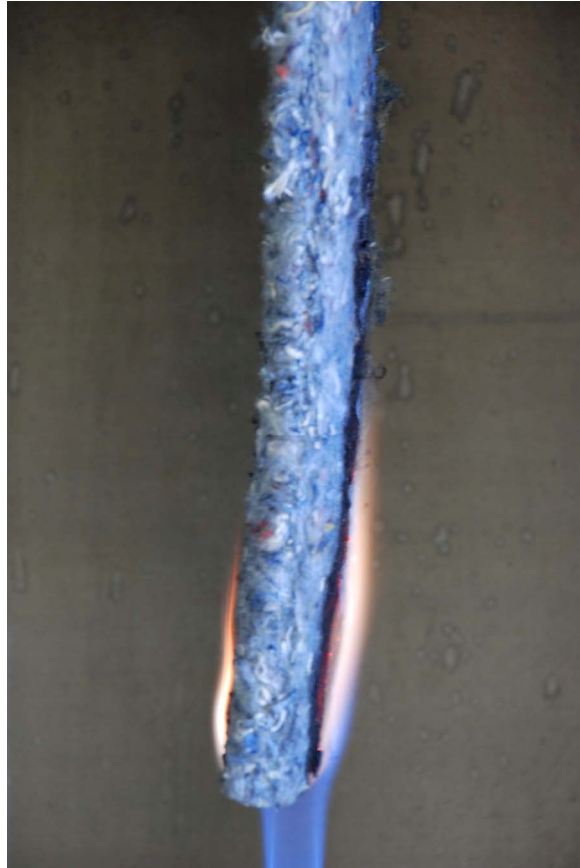Picture times from right to left, top to bottom:
0 s - 10 s - 15 s
23 s - 35 s - 43 s
48 s - 51 s - 71 s

Figure 4.4. Photographs of FR Material vertical flame spread test

In the bottom of the figure, the total test duration and time elapsed for each picture

(moving left to right and top to bottom) is listed. After 71 seconds of flame

impingement, the material still had yet to exhibit any signs of flame spread. Even after

increasing the flame height to almost 3 times its initial height by adjusting the flow of methane to the burner, flame spread did not occur. More charring over a larger area did take place, but only due to the increased size of the ignition source. In Figure 4.5, a photograph of the increased flame size with no flame spread is shown.
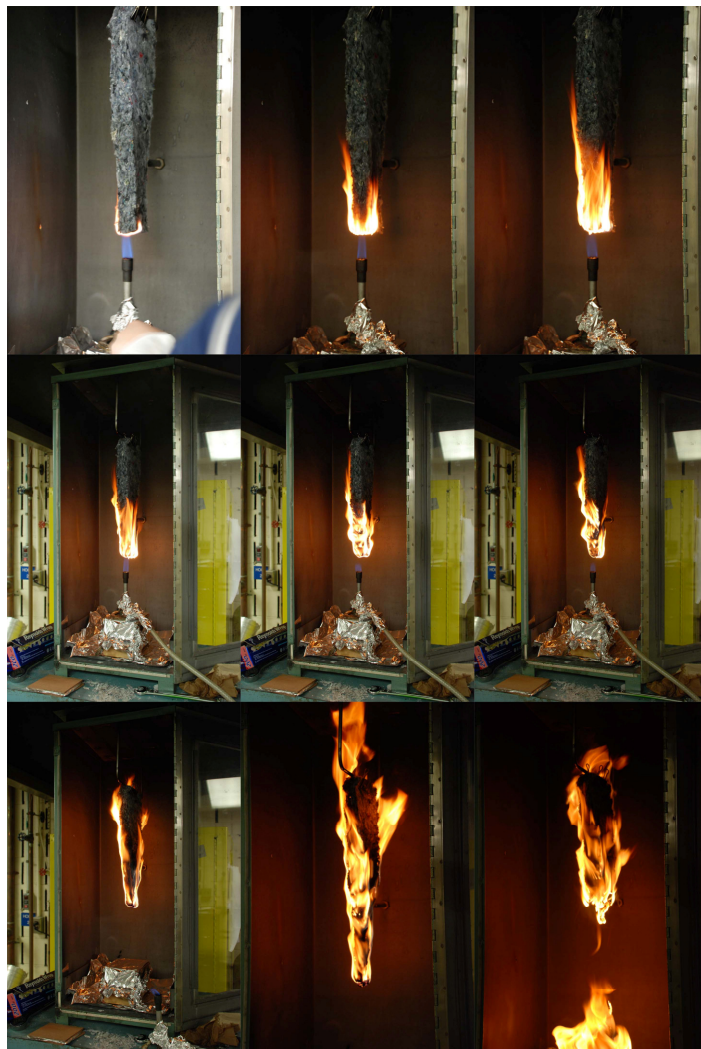

Figure 4.5. Photograph of FR Material vertical flame spread test with increased flame size

Though no parameters were given for failure or success in this test, FR Material sample was resistant to ignition and flame spread in the vertical orientation in these tests.

- **Current Material**

The Current Material sample ignited quickly and propagated flames upward along the sample. Once ignited, the flames grew larger and accelerated up the height of the sample. These results are shown in the photographs in Figure 4.6.

Test Duration: 37 seconds

Picture times from right to left, top to bottom:
0 s - 5 s - 10 s
16 s - 21 s - 24 s
33 s - 35 s - 37 s

Figure 4.6. Photographs of FR Material vertical flame spread test

In the bottom of the figure, the total test duration and time elapsed for each picture (moving left to right and top to bottom) is listed. After 5 seconds, the sample has clearly ignited and flame spread has begun. By the 33 second mark, the entire sample has become involved and by 37 seconds the sample is no longer able to support its own weight, resulting in the separation of the burning material into multiple parts; NFPA 556 requires that materials not have this characteristic of flaming drips or the separation of flaming parts. In other runs of this same test with the Current Material sample, full sample involvement sometimes occurred in as little as 15 seconds. In the vertical modified-FMVSS 302 test, the Current Material sample did not perform well. Even without a comparison to the FR Material sample, it is evident that the Current Material lacks fire retardancy for use in the vertical orientation.

4.2.1.3 Review of Horizontal and Vertical Flame Spread Results
The cumulative results from all four tests indicate that the FR Material sample is superior to the Current Material sample in resistance to ignition and flame spread in both the horizontal and vertical orientations under ambient conditions. Although no flame spread parameters were applied to the vertical test, the FR Material sample visibly performed well while the Current Material sample did not. In the horizontal tests, the FR Material sample passed the standard's requirements with a flame spread velocity of less than 5 mm/min while the Current Material sample did not pass with a flame spread velocity of approximately 110 mm/min.

4.2.2 Bench-scale Tests Results

In the bench-scale tests, the cone calorimeter was used to obtain data on the ignition and burning properties, critical incident heat fluxes, heat release rates, and interface temperatures for the two materials. The two materials were exposed to incident heat fluxes of 15, 25, and 50 kW/m^2 and various measurements and recordings were made. The results from these tests follow, in order of incident heat flux, lowest to highest. They consist of the heat release rate of ignited samples and interface temperatures.

4.2.2.1 15 kW/m^2 Incident Heat Flux Test Results

In these tests, the samples were exposed to an incident heat flux of 15 kW/m^2. For each sample, three tests were conducted at the incident heat flux. The heat release rates and interface temperatures for these samples were recorded and plotted versus time. In the following sections, these plots are shown.
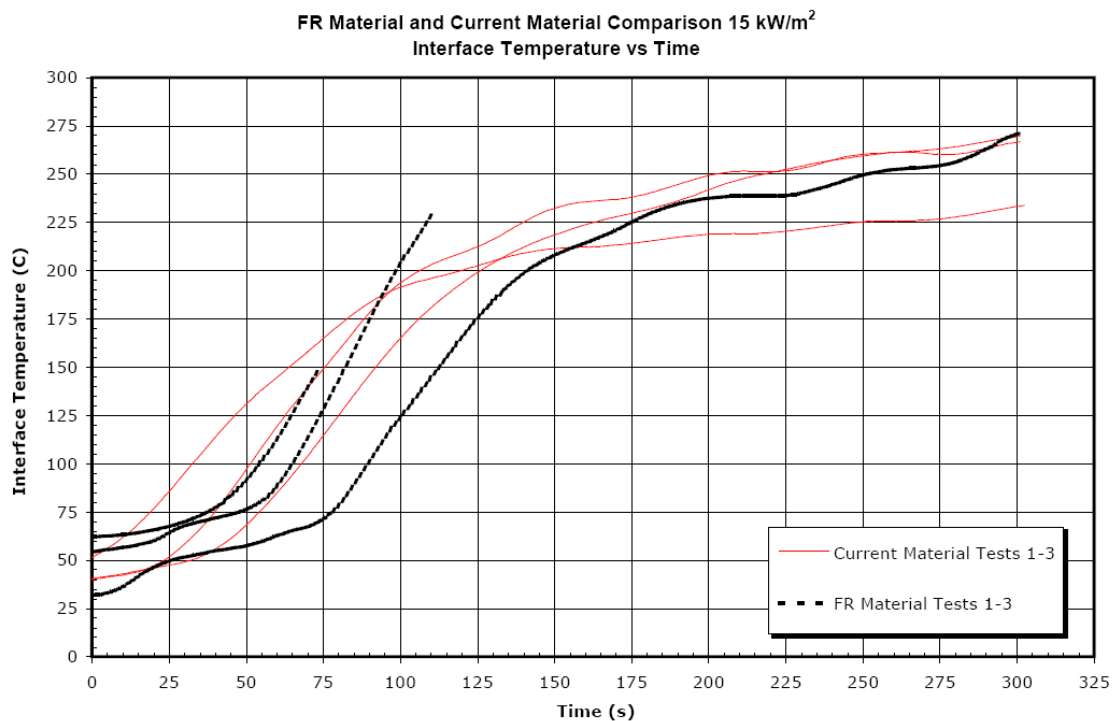
- **Heat Release Rate**

The HRR results from the three tests for each sample at an incident heat flux of 15 kW/m^2 are presented in Figure 4.7. The two FR Material HRR curves that spike are due to ignition during those two tests, while the other four curves represent tests in which ignition did not occur. The sample of FR Material that did not ignite has a comparable HRR pattern to the non-ignition Current Material samples. These tests indicate that the FR Material material appears to have a lower critical heat flux for ignition than the Current Material.
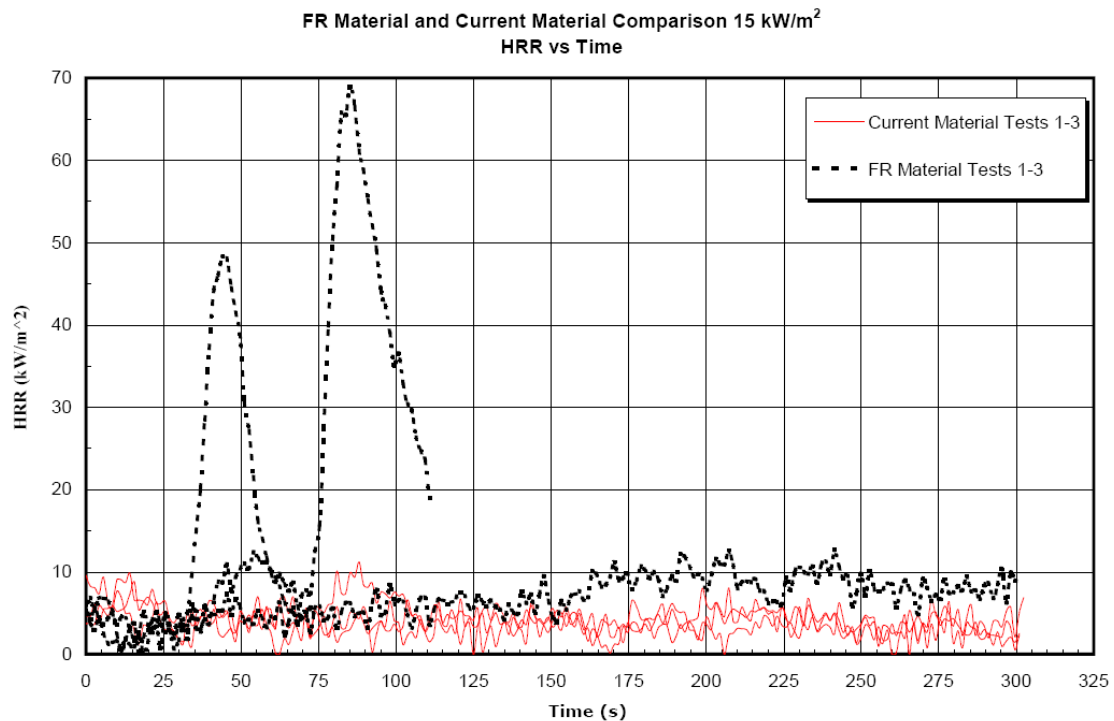
Figure 4.7. HRR at 15 kW/m^2 for both samples

- **Interface Temperature**

The interface temperature results from the three tests for each sample at an incident heat flux of 15 kW/m^2 are presented in Figure 4.8. The two plots with steeper temperature increases are from the two FR Material tests in which ignition occurred. The two samples have similar insulation qualities, with the FR Material samples peaking at a slightly higher temperature due to ignition.

Figure 4.8. Interface temperatures at 15 kW/m^2 for both samples
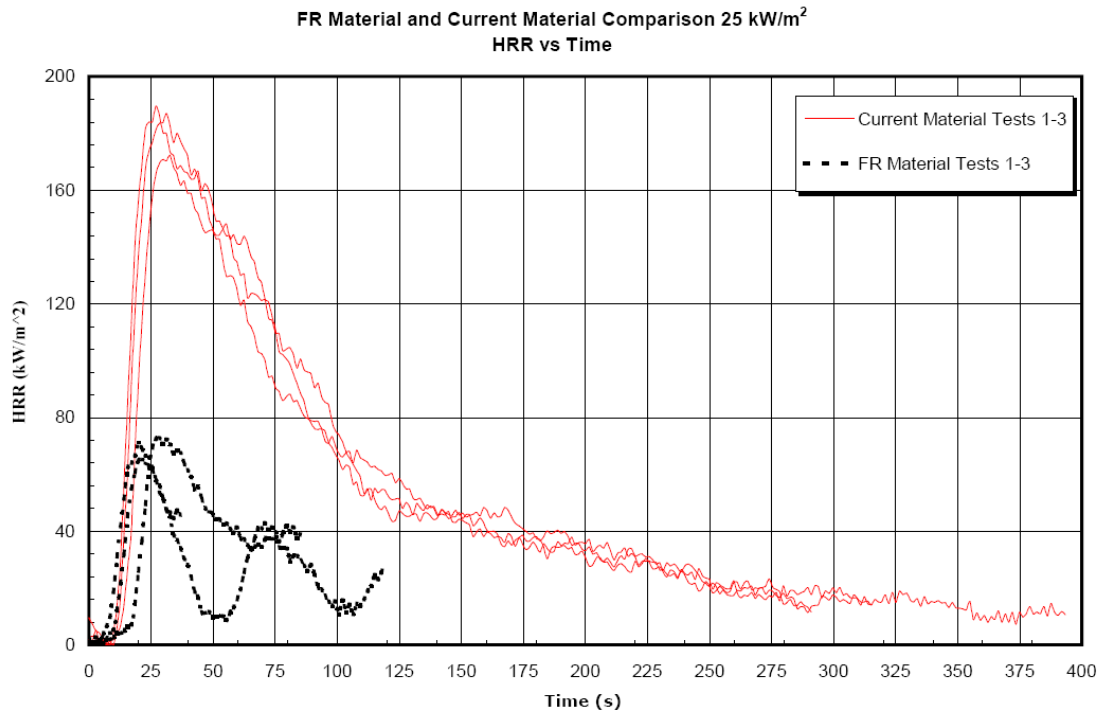
4.2.2.2 25 kW/m^2 Incident Heat Flux Test Results

In these tests, the samples were exposed to an incident heat flux of 25 kW/m^2. For each sample, three tests were conducted at the incident heat flux. The heat release rates and interface temperatures for these samples were recorded and plotted versus time. In the following sections these plots are shown.

- **Heat Release Rate**

The HRR results from the three tests for each sample at an incident heat flux of 25 kW/m^2 are presented in Figure 4.9. The curves from the two samples share similar shape, indicating somewhat similar ignition and burning while their peak heat release rates differ. The peak heat release rate from the FR Material samples is approximately 72 kW/m^2 while the Current Material samples have peak heat release rates of approximately 180 kW/m^2.

Figure 4.9. HRR at 25 kW/m^2 for both samples

- **Interface Temperature**

The interface temperature results from the three tests for each sample at an incident heat flux of 25 kW/m^2 are presented in Figure 4.10. Tests were stopped once the samples self-extinguished, accounting for the shortened time measurements of the FR Material tests. Although a complete comparison can not be made, it appears as though the FR Material exhibits better insulative properties than the Current Material within the first 110 seconds.

Figure 4.10. Interface temperatures at 25 kW/m^2 for both samples

4.2.2.3 50 kW/m^2 Incident Heat Flux Test Results
In these tests, the samples were exposed to an incident heat flux of 50 kW/m^2.
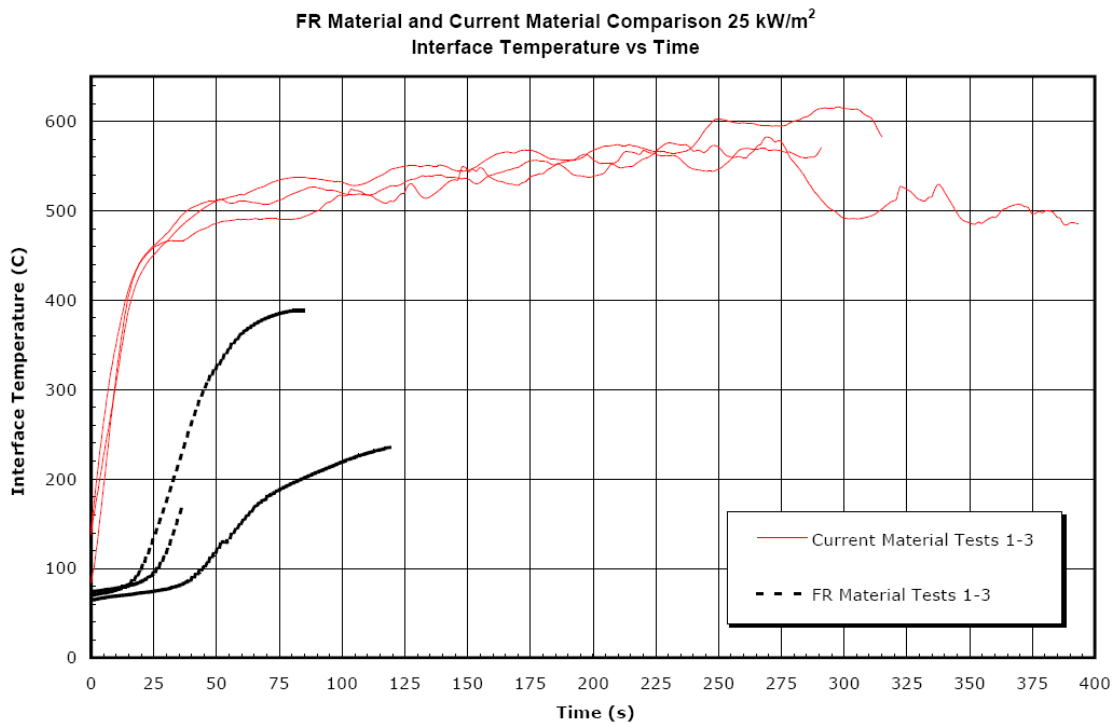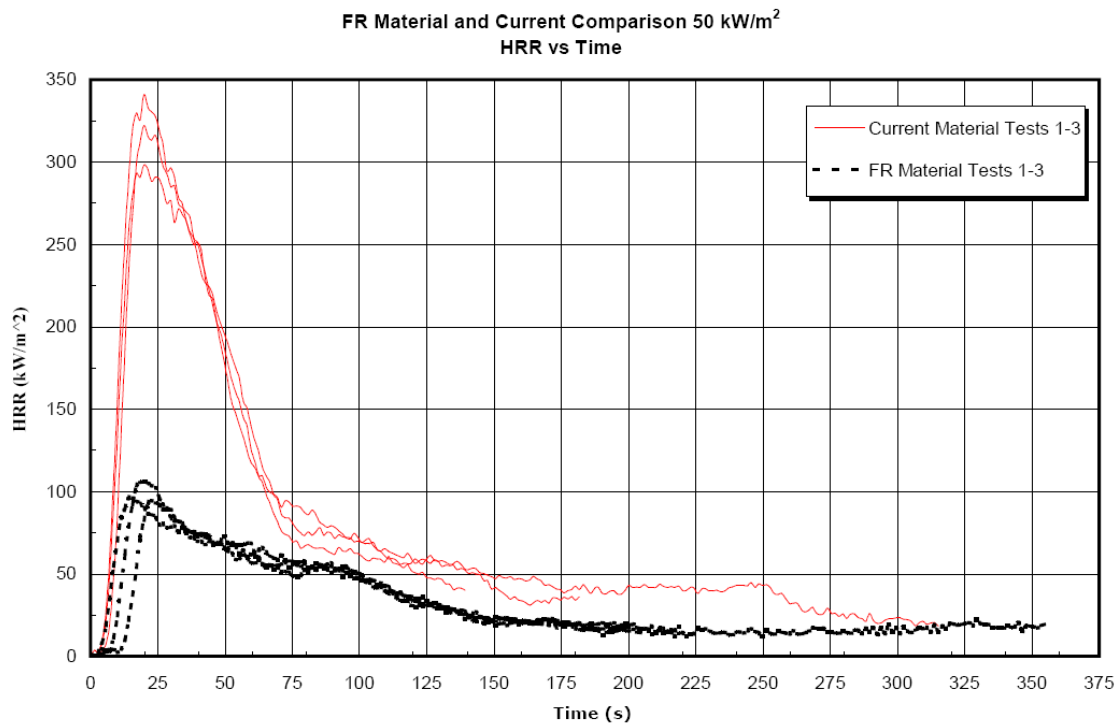
- **Heat Release Rate**

The cumulative HRR results from the three tests for each sample at an incident heat flux of 50 kW/m^2 are presented in Figure 4.11. The curves from the two samples share similar shape, indicating somewhat similar ignition times while their peak heat release rates differ.   The peak heat release rate from the FR Material samples is approximately 100 kW/m^2 while the Current Material samples have peak heat release rates of approximately 310 kW/m^2.

Figure 4.11. HRR at 50 kW/m^2 for both samples

- **Interface Temperature**

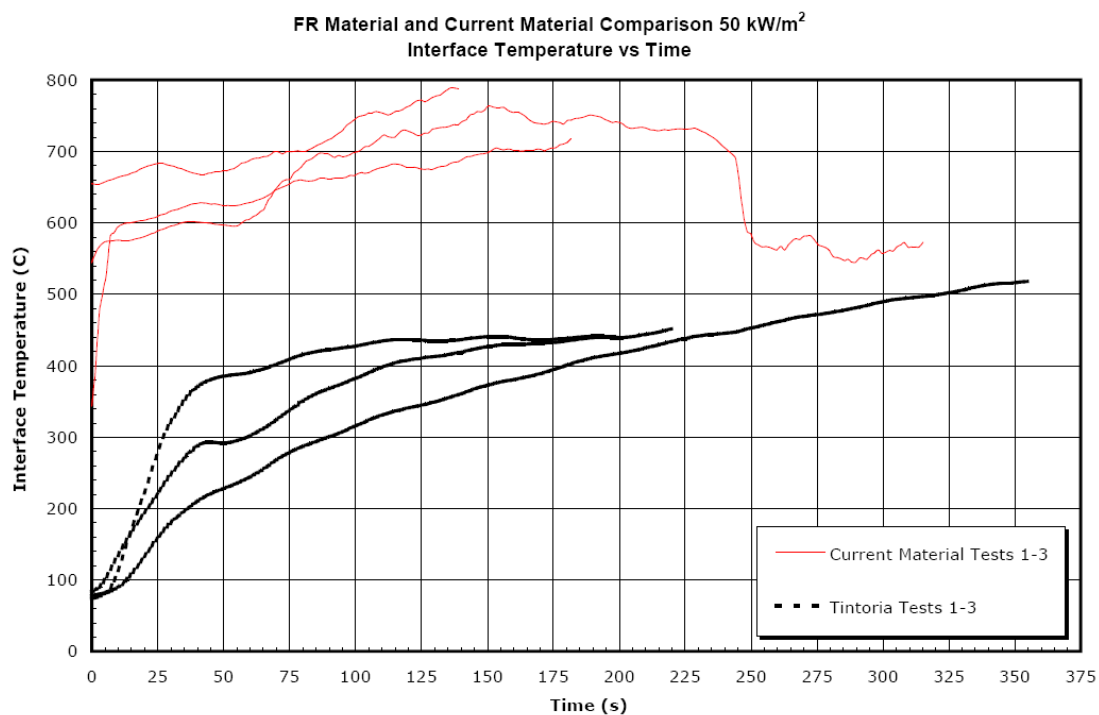The interface temperature results from the three tests for each sample at an incident heat flux of 50 kW/m^2 are presented in Figure 4.12. From the figure, the FR Material samples prevented considerable heat from penetrating to the steel backing 40 seconds longer than the Current Material samples. Additionally, the FR Material samples keep the peak temperature of the steel backing at almost 300°C less than the Current Material samples.

Figure 4.12. Interface temperatures at 50 kW/m^2 for both samples

4.2.2.4 Review of Ignition, Burning, HRR, Critical Incident Heat Flux, and Interface Temperature Results
Based on the data collected and the observations made during the bench-scale tests, the

following sections outline the results from the all the bench-scale tests as a whole.

- **Ignition**

From the small-scale tests, the materials' resistance to ignition at room temperature was observed; unfortunately, in the real-world environment, these insulation samples will not always be exposed to pilot flames under ambient conditions. In the bench-scale tests, the materials' ignition properties at incident heat fluxes were able to be observed. Table 4.1 shows the ignition results from the 15, 25 and 50 kW/m^2 incident heat flux bench-scale tests.

Heat Flux/Test	Current Material	FR Material
	Ignition?	
15 kW/m^2 / 1	No	No
15 kW/m^2 / 2	No	Yes
15 kW/m^2 / 3	No	Yes
25 kW/m^2 / 1	Yes	Yes
25 kW/m^2 / 2	Yes	Yes
25 kW/m^2 / 3	Yes	Yes
50 kW/m^2 / 1	Yes	Yes
50 kW/m^2 / 2	Yes	Yes
50 kW/m^2 / 3	Yes	Yes

Table 4.1. Ignition Results for Current Material and FR Material Samples

At 15 kW/m^2, two of the FR Material samples ignited at 68 and 28 seconds, while the Current Material samples did not. All samples beyond this heat flux ignited within 10 seconds; at high heat fluxes, ignition could occur in as little as 3 seconds. This short ignition time occurs because of the low density nature of the samples.

- **Burning**

Upon ignition, it is important to observe the flaming characteristics of the materials. In the vehicle environment, these flames will impinge upon other materials in the vehicle;

thus, an understanding of the severity at which these samples burn is helpful in determining how surround materials will be effected.

Flames in the burning Current Material samples were greater in height than those exhibited in the FR Material samples; these flames were more turbulent as well. Burning periods were shorter for the FR Material and after the surface of the material was charred, combustion soon ceased. The Current Material burned more fully and mass loss was greater.

A comparison between the times until burn out in the 15 kW/m^2 samples is not possible because the only two samples to ignite were two of the FR Material samples; at 25 kW/m^2, the time until burnout in the FR Material samples was significantly less than that of the Current Material; and at 50 kW/m^2, the burn duration of the two sample types was comparable. Table 4.2 lists the time durations for burning for each of the tests. For test 3 at an incident heat flux of 25 kW/m^2, after burning out the first time, the sample was able to be reignited twice. These times are indicated in the table as well.

Burn Duration (s)				
Heat Flux	Material	Test 1	Test 2	Test 3
15 kW/m^2	Current Material	-	-	-
	FR Material	-	32	17
25 kW/m^2	Current Material	305	264	358
	FR Material	53	48	23, 20, 20
50 kW/m^2	Current Material	308	157	201
	FR Material	208	343	180

Table 4.2. Burn Durations for Bench Scale Tests

The Current Material samples, when ignited, would burn until most of the material had burnt away; upon extinction of the flame, very little of the samples remained. Figures 4.13, 4.14, and 4.15 show the extent of this degradation as the incident heat flux is increased.
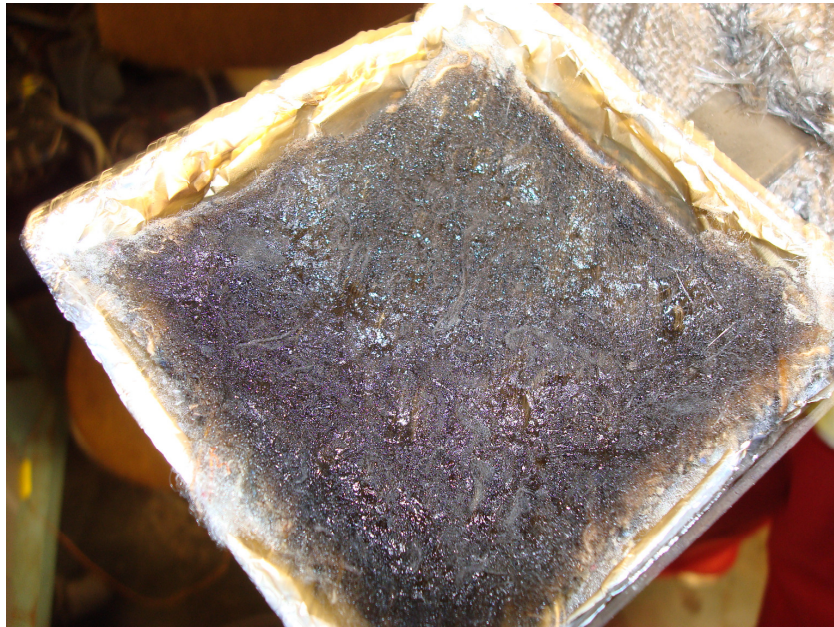
Figure 4.13. Current Material after 15 kW/m^2

Figure 4.14. Current Material after 25 kW/m^2
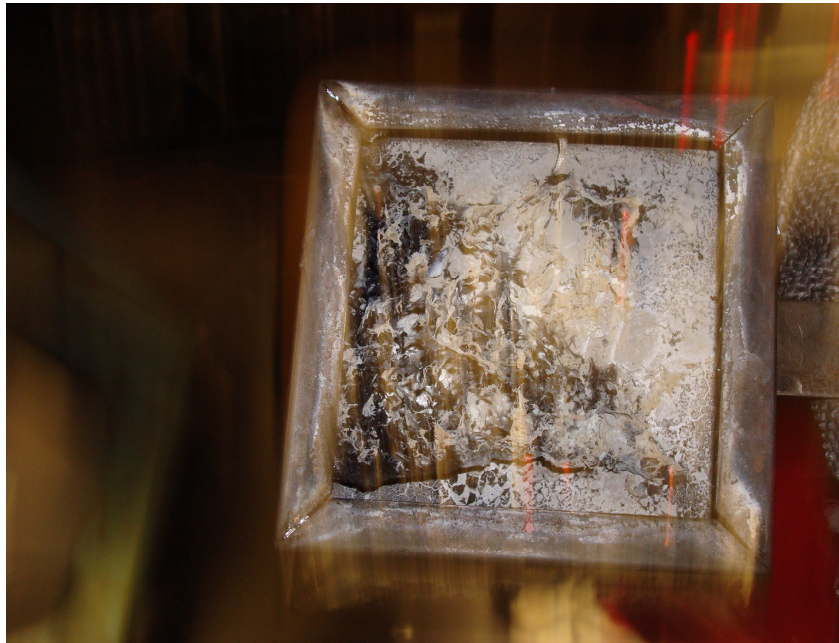
Figure 4.15. Current Material after 50 kW/m^2

As these samples burned and lost mass, they in turn began to lose their insulative quality.

The high interface temperatures in the Current Material samples can be partially

attributed to this mass loss. In Figure 4.15, the white area in the upper right triangle is

the steel underneath the sample. In this case, very little of the sample remains after the

burn. The FR Material samples charred on the surface, and depending upon the length of

burn, would sometimes char lower into the sample, but the material would maintain

shape and integrity. Figures 4.16, 4.17, and 4.18 show the charring in the FR Material

samples as the incident heat flux is increased.

Figure 4.16. FR Material after 15 kW/m^2

Figure 4.17. FR Material after 25 kW/m^2
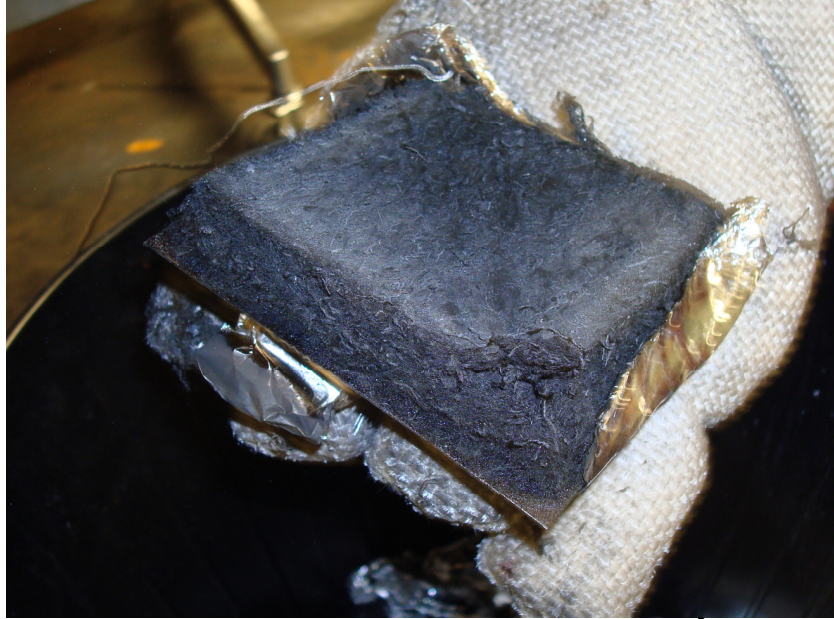
Figure 4.18. FR Material after 50 kW/m^2

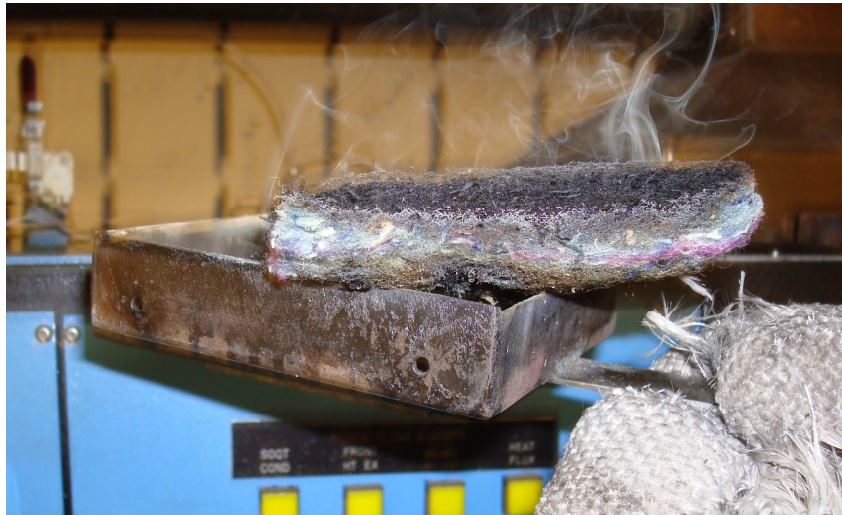There are clear differences between the Current Material sample remains in Figure 4.15 and the FR Material sample remains in Figure 4.18. Though the FR Material has been affected by the incident heat and ignition, it retains more of its mass and thus retains more of its insulative qualities.

- **Critical Heat Flux**

Critical heat flux tests using the cone calorimeter resulted in critical heat fluxes for the FR Material and Current Material insulation samples, respectively, of 16.5 kW and 18.5 kW. In multiple tests, the Current Material's critical heat flux was consistently 2 kW greater than the FR Material samples. This could be due to several factors, such as material density, composition, and additives.

- **Heat Release Rate**

The heat release rates are critical to assessing the fire performance of a material. As stated in Section 2.1.3, heat is the primary killer in vehicle fires because of the enclosed passenger compartment. A product with a lower heat release rate (along with other pertinent qualities) can be expected to lower the risk of injury or death to a vehicle occupant in the event of a fire.

At 15 kW/m^2, two of the FR Material samples ignited, resulting in heat release rates while the other FR Material sample and Current Material samples, which did not ignite, do not have heat release rates. Other than the incident heat flux of 15 kW/m^2, the FR Material samples had lower heat release rates than the Current Material samples; at 25 kW/m^2 and 50 kW/m^2, the Current Material samples had higher heat release rates than the FR Material samples. Table 4.3 shows the peak and average heat release rates (HRR) in kW/m^2 for all tests.

Heat Flux / Test	Current Material		FR Material	
	Peak HRR (kW/m^2)	Average HRR (kW/m^2)	Peak HRR (kW/m^2)	Average HRR (kW/m^2)
15 kW/m^2 / 1	N/A	N/A	N/A	N/A
15 kW/m^2 / 2	N/A	N/A	69.9	17.3
15 kW/m^2 / 3	N/A	N/A	48.3	13.2
25 kW/m^2 / 1	187.0	89.5	72.7	41.2
25 kW/m^2 / 2	189.6	88.4	65.1	41.3
25 kW/m^2 / 3	172.3	87.5	71.2	28.9
50 kW/m^2 / 1	322.1	106.3	94.6	48.1
50 kW/m^2 / 2	298.1	125.1	95.9	54.5
50 kW/m^2 / 3	340.8	133.5	105.9	54.8

Table 4.3. Peak and Average HRR

From the values shown here, the FR Material samples performed better in terms of heat release rate at higher heat fluxes. At 25 kW/m^2 and 50 kW/m^2, the FR Material samples

had HRR's of less than half that of the Current Material; it was found that the peak HRR

of the Current Material was an average of 2.36 times higher than the FR Material samples

and the average HRR was an average of 1.25 times higher. Figures 4.19, 4.20, and 4.21

give a graphical representation of this data for a better comparison of magnitude.
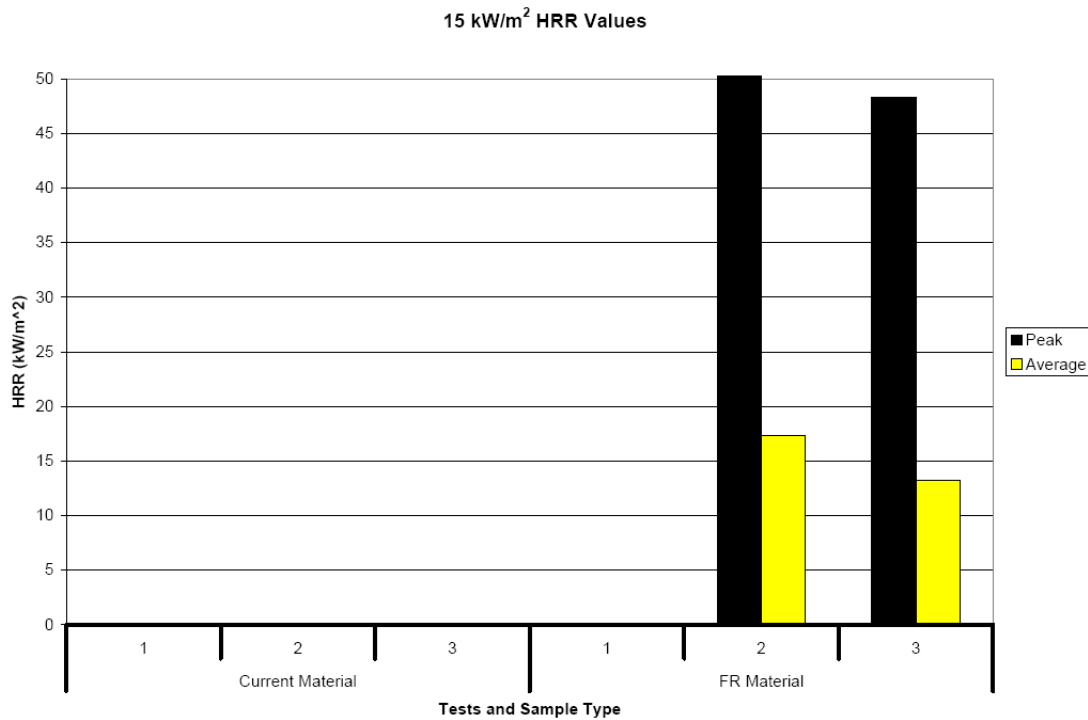
Figure 4.19. Side-by-side Comparison of 15 kW/m^2 HRR Values
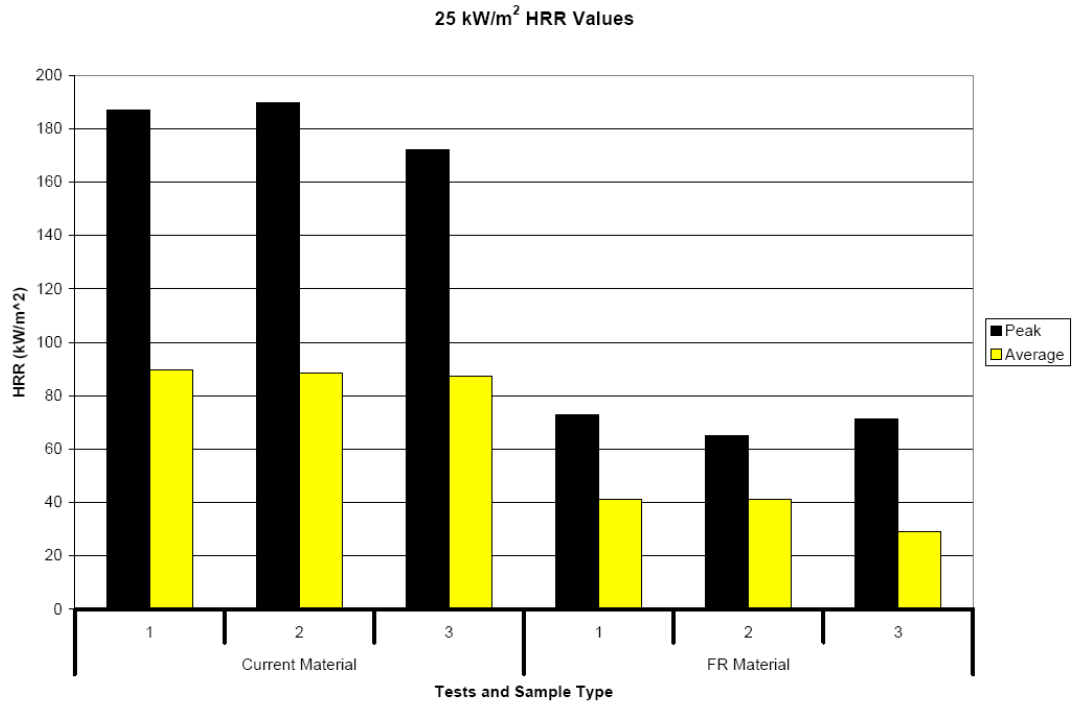
Figure 4.20. Side-by-side Comparison of 25 Kw/m^2 HRR Values
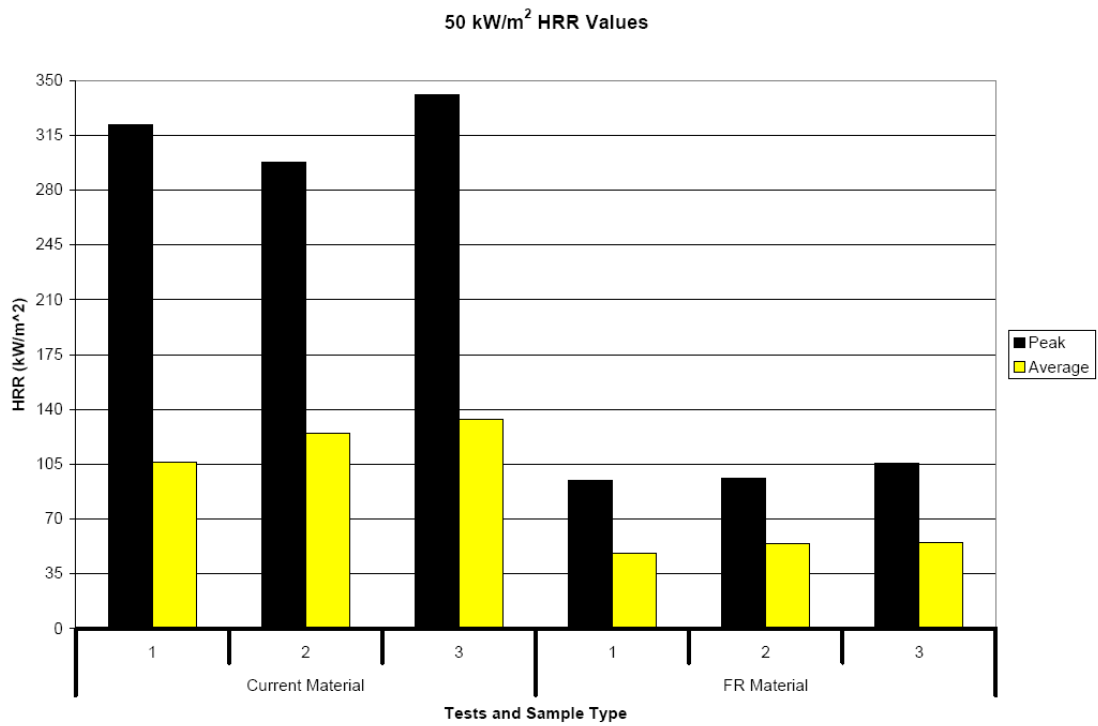
Figure 4.21. Side-by-side Comparison of 50 kW/m^2 HRR Values

- **Interface Temperature**

At 15 kW/m^2, the two sample types had comparable performance in insulating the thermocouple from the incident heat flux. As the heat flux was increased, the superior performance of the FR Material samples over the Current Material samples was evident. At both 25 kW/m^2 and 50 kW/m^2, the FR Material samples were better insulators than the Current Material, with performance increasing with relative heat fluxes. Table 4.4 lists the peak interface temperatures for all tests of both samples.

Peak and Average Temperatures (°C) at the Interface			
		FR Material	**Current Material**
Heat Flux	**Test #**	**Peak Temp (°C)**	**Peak Temp (°C)**
15 kW/m^2	1	271	267
	2	231	270
	3	150	234
25 kW/m^2	1	388	616
	2	175	570
	3	235	582
50 kW/m^2	1	452	764
	2	518	789
	3	441	718

Table 4.4. Peak Interface Temperatures

Figures 4.22, 4.23, and 42.4 give a graphical representation of this data for a better comparison of magnitude.

15 kW/m^2 Interface Temperature Values
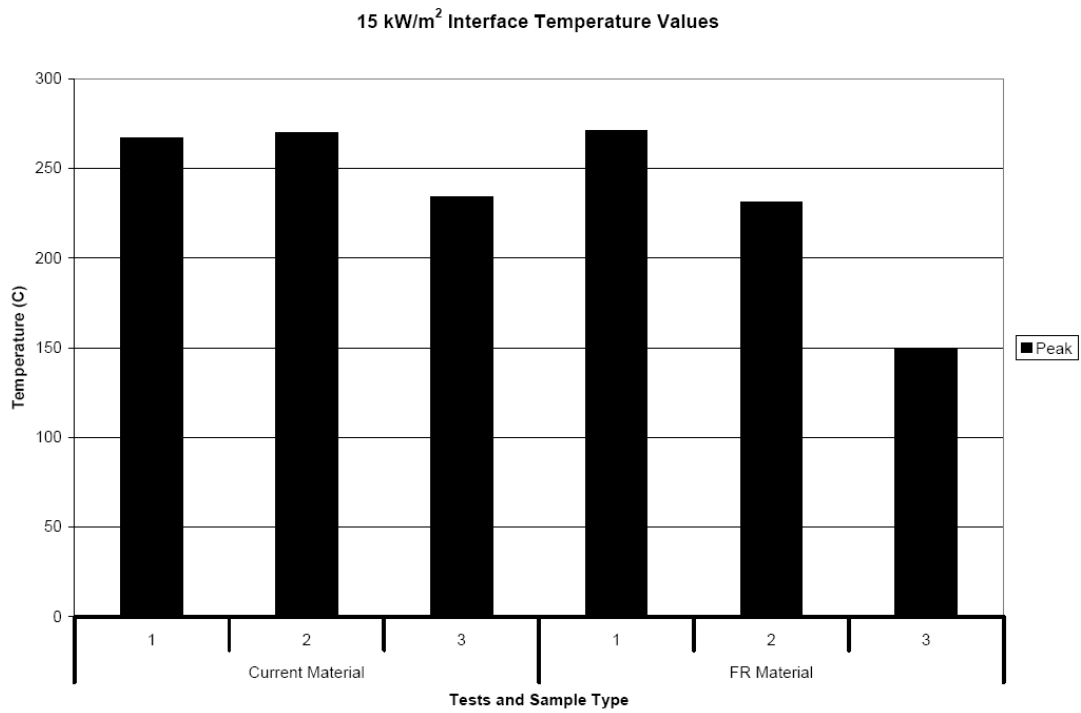
Figure 4.22. Side-by-side Comparison of 15 kW/m^2 Interface Temperatures

25 kW/m^2 Interface Temperature Values
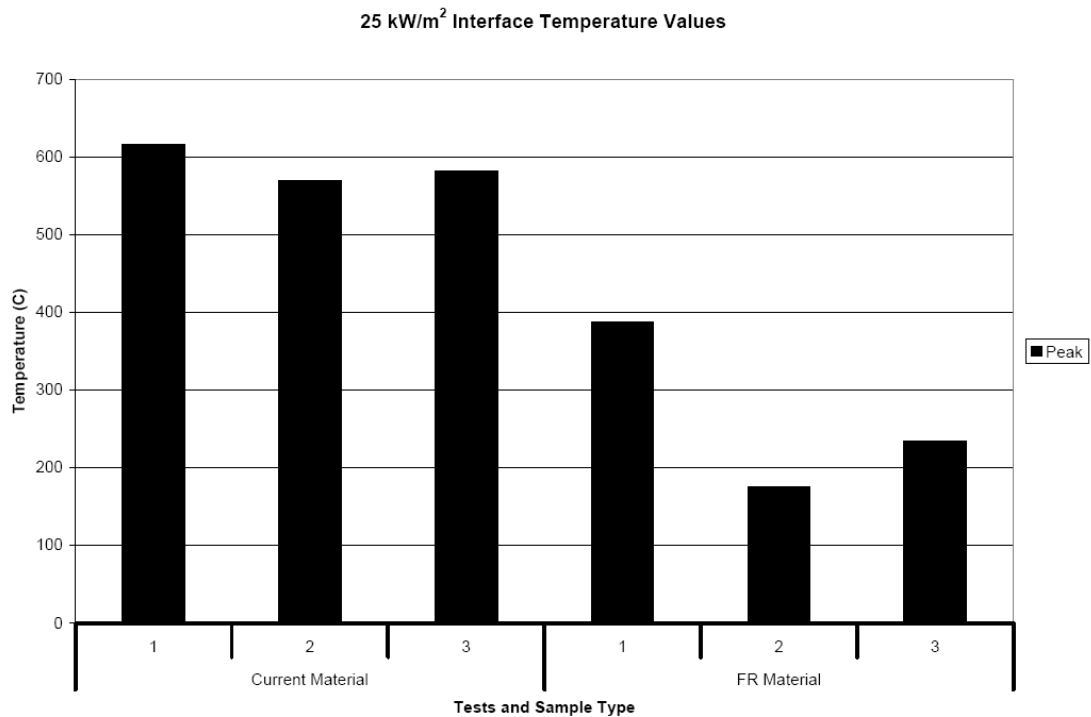
Figure 4.23. Side-by-side Comparison of 25 kW/m^2 Interface Temperatures
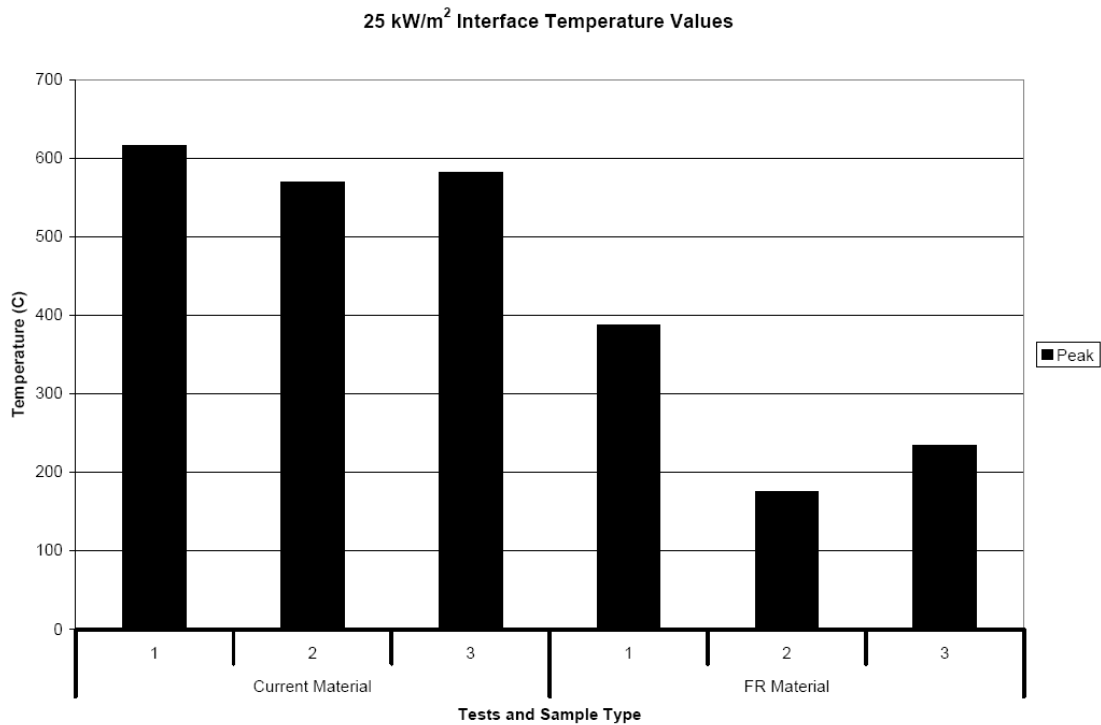
Figure 4.24. Side-by-side Comparison of 50 kW/m^2 Interface Temperatures

- **Bench-scale Tests Overview**

The bench-scale results were conclusive in that the FR Material has superior burning,

HRR, and insulative qualities in comparison to the Current Material. Ignition properties

are relatively even between the two samples, but the critical heat flux of the FR Material

is lower than that of the Current Material. In the presence of an incident heat flux 15

kW/m^2 and greater, the two materials have similar times to ignition.

4.2.3 Large-scale Tests

The large-scale tests were used to obtain data concerning the effectiveness of the

acoustical insulation in a true-to-life vehicle fire scenario.

4.2.3.1 General Experiment Observations
- **Insulation Installation**

During the insulation replacement process, it was observed that little insulation was

actually used in the firewall. Figures 4.24 and 4.25 from the Dodge Neon show that the

insulation does not reach the top of the carpeting in the footwell; it was initially believed

that the insulation reached all the way behind the dashboard. This fact will be taken into

consideration when analyzing the results. Additionally, in the Infiniti, there was very

little firewall insulation, at least of any sort similar to the insulation of FR Material and

Current Material; a dense, yellow foam was used instead. The FR Material insulation

was installed under the material (the foam was glued securely to the carpeting and could

not be removed) and in dashboard areas.

Figure 4.25. Current Material pre-removal of old insulation

Figure 4.25. Current Material pre-removal of old insulation

- **Current Material Test: Dodge Neon**

In the first test, the Dodge Neon front end was facing into the wind. The front passenger door was left open to allow views inside the vehicle during the test. Upon significant involvement of the engine compartment, the winds on the day of the test (average wind speed was 11.9 mph, with gusts of up to 30 mph) pushed the flames from the engine compartment around the open door and into the passenger compartment. This made it difficult to tell if flames had penetrated through the duct work or the fire wall. After flames were observed in the passenger compartment, the test was terminated and the fire was extinguished by MFRI personnel.

- **FR Material Test: Infiniti J30**

In the second test, the Infiniti J30 front end was facing away from the wind. Rather than drawing the flames back toward the vehicle, flames were pushed ahead of the vehicle; this allowed the engine compartment fire to propagate more normally through the engine compartment. Wind speeds for this test were high as well, as shown in Figure 4.26.

Once flames entered the passenger compartment, the test was terminated and the fire was

extinguished by MFRI personnel.

Figure 4.26. Wind effects on FR Material

4.2.3.2 Passenger and Driver Side Temperature Measurements and Observations
The following Sections [4.2.3.2.1 to 4.2.3.2.4] provide plotted temperature data for the

passenger and driver side thermocouples for each of the two tests. They should be used

to understand the temperature variation from the engine compartment to the passenger

compartment as well as the variation between the passenger and driver side of the

vehicles. Ignition occurs at the 0-second mark.

- **Current Material Driver Side**

Figure 4.27 shows the driver side temperatures measured in the Current Material vehicle

fire. Engine compartment temperatures are highest, followed by the dashboard; these

results correlate with findings from previous research reviewed in Chapter 2.
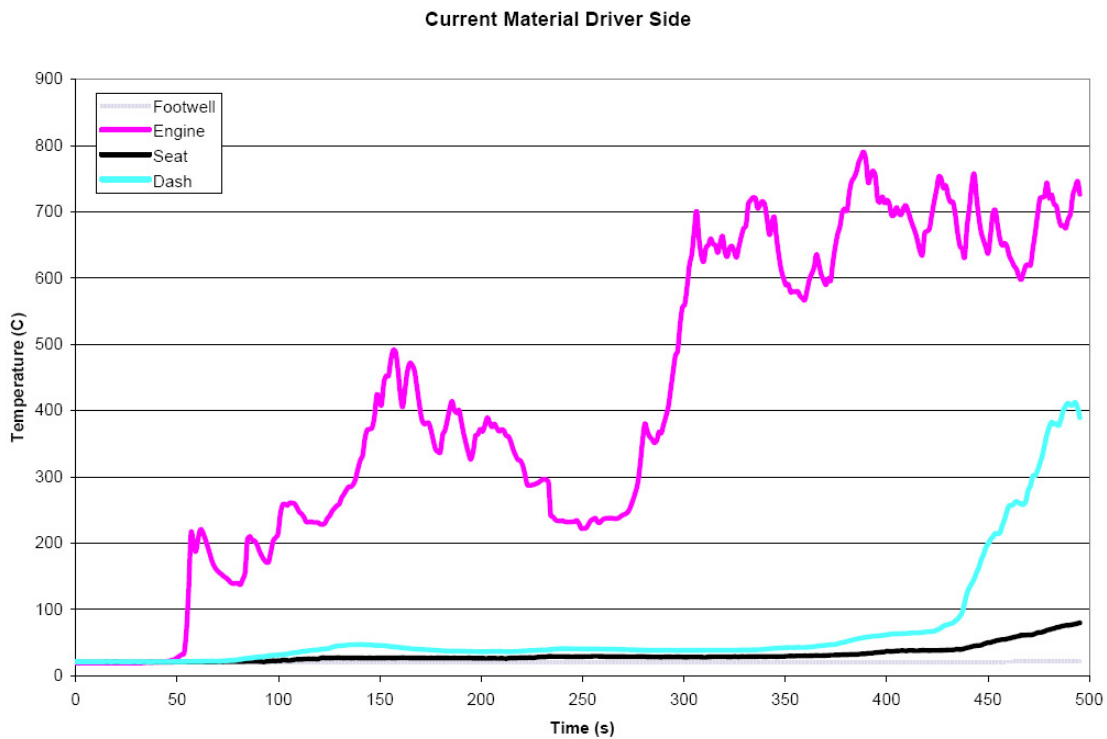
Figure 4.27. Current Material Driver Side Temperature Results

- **Current Material Passenger Side**

Figure 4.28 shows the passenger side temperatures measured in the Current Material vehicle fire. As can be assumed, engine compartment temperatures are highest for most of the test. The spike in seat temperature at approximately 455 seconds is related to the entry of flames into the passenger compartment; this will be discussed further in the results section.

Figure 4.28. Current Material Passenger Side Temperature Results

- **FR Material Driver Side**

Figure 4.29 shows the driver side temperatures measured in the FR Material vehicle fire. These results exhibit more variation than the Current Material results; this can possibly be attributed to the difference in flame propagation [as compared to the Current Material test] through the engine compartment caused by the high winds. From the temperatures, it is clear that flames and heat found their way into the driver side of the passenger compartment resulting in high footwell and seat temperatures. This will be discussed further in the results section.

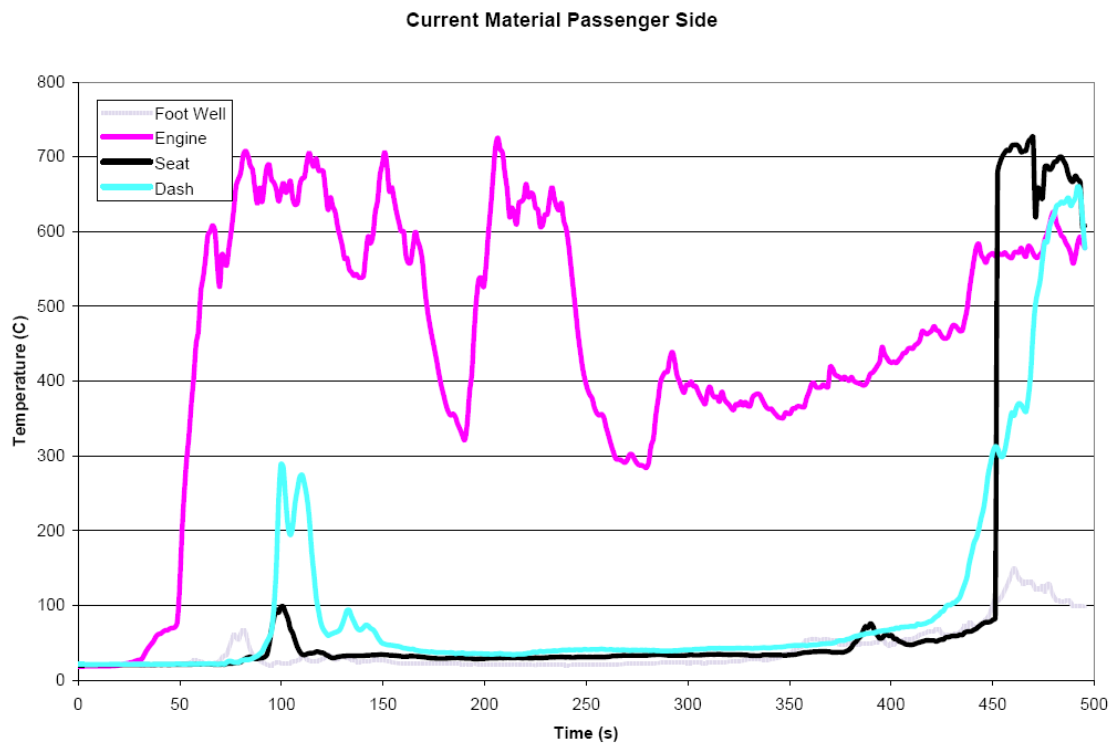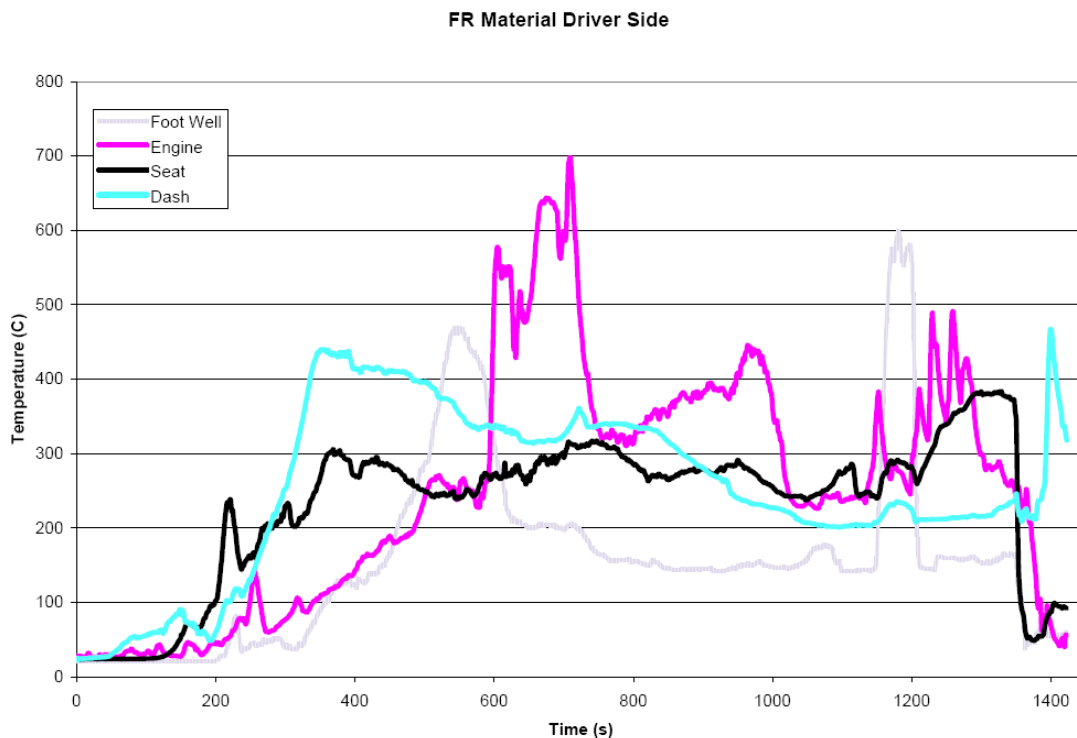**Figure 4.29. FR Material Driver Side Temperature Results**

- **FR Material Passenger Side**

Figure 4.30 shows the passenger side temperatures measured in the FR Material vehicle fire. Engine compartment temperatures are highest. The dashboard and seat temperatures both exhibit odd behavior; the readings are low until 1215 seconds where spikes occur in both, followed by a gradual decay period, then another spike in temperature at 1395 seconds. Individually, these results could be questioned because of their odd shape, but because they both follow the same pattern, their shape can possibly be attributed to flame entry into the passenger compartment. As discussed further in the results section, flames were observed entering the passenger compartment, supporting this hypothesis.
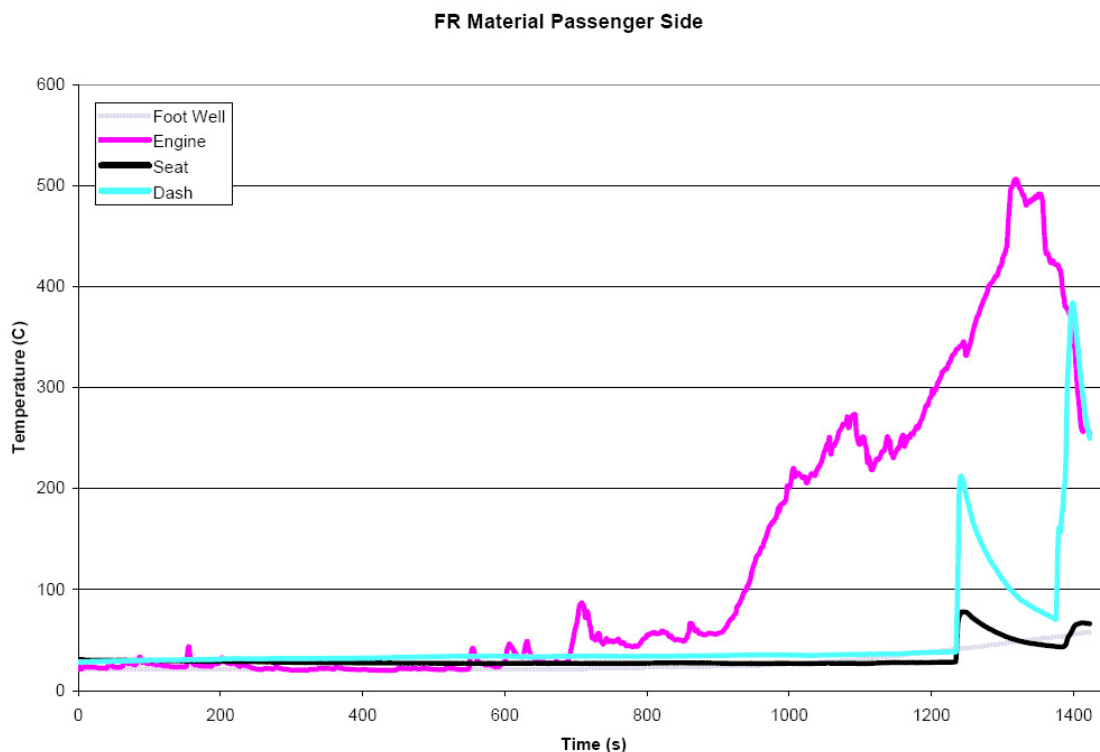
Figure 4.30. FR Material Passenger Side Temperature Results

4.2.3.3 Zoned Temperature Measurements, Observations, and Comparisons

In the following Sections [4.2.3.3.1 to 4.2.3.3.4], temperature results for the four zones of

thermocouple measurements are presented. These zones are:

- Engine compartment

- Footwell

- Dashboard

- Occupant seating area

The plots include measurements from the passenger and driver side of each test, so as to

provide a comparison between the FR Material and Current Material tests as well as a

comparison between temperatures in the lateral direction (driver side to passenger side).

- **Engine Compartment**

Current Material & FR Material Engine Compartment Temperatures
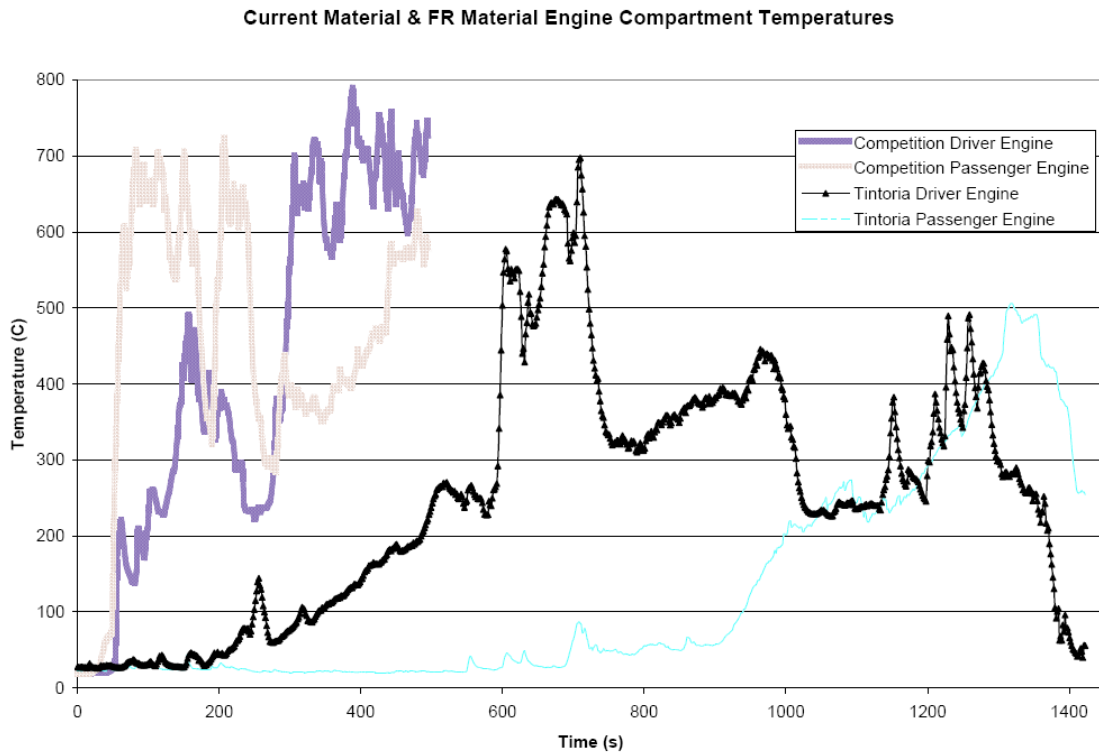
Figure 4.31. FR Material and Current Material Engine Compartment Temperatures

From Figure 4.31, the temperature results show that the engine compartment measurements for the Current Material burn are fairly similar to one another in the medial direction (engine to passenger compartment). They begin peaking within a minute of each other; this delay can be associated with the packing of the Excelsior as well as the size and orientation of the engine. The FR Material test, on the other hand, does not correlate well in the medial direction. Although the two plots share very similar shape, the driver side engine thermocouple begins its ascent at around 200 seconds while the passenger engine thermocouple begins its ascent at around 650 seconds. It is interesting that they share similar shape, which would indicate similar flame propagation; nearly eleven (11) minutes would pass before flames reached the passenger engine thermocouple. One explanation could be the wind effects; if the winds were impacting the vehicle toward the driver side of the vehicle, more air would be made available to the driver side, increasing fire size and thus temperatures.

- **Footwell**
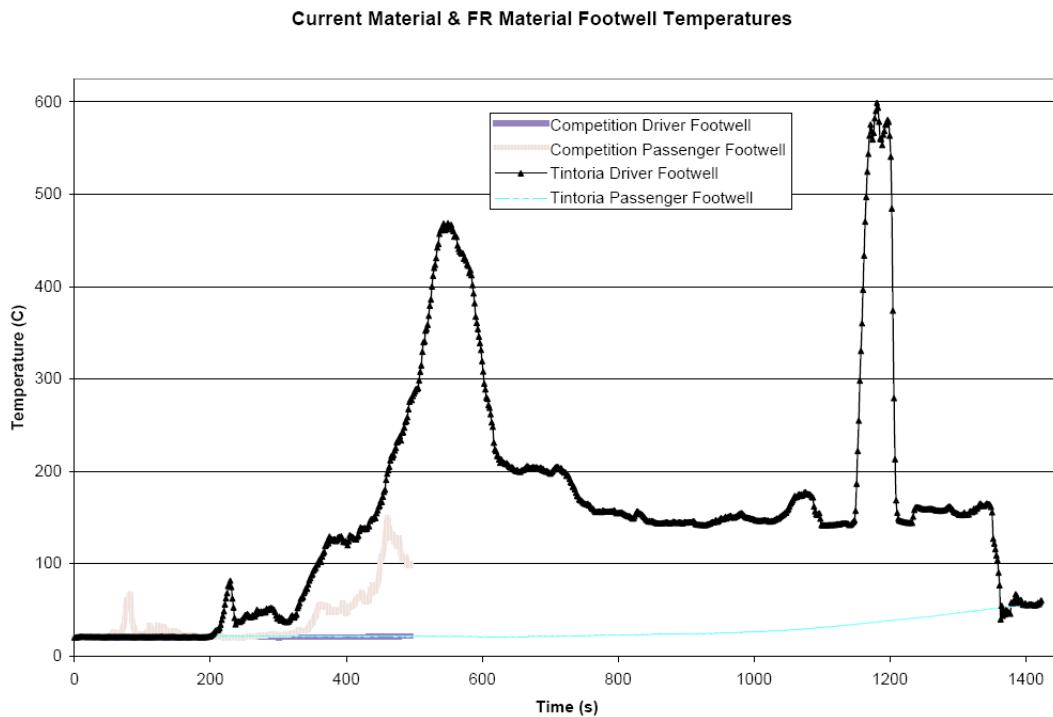
Figure 4.32. FR Material and Current Material Footwell Temperatures

In the Current Material test, due to the open door, a rise in footwell temperature was observed while the driver side footwell showed little if any increase in temperature, shown in Figure 4.32. The increase in the footwell temperature can be expected due to the flame travel through the open door. For the FR Material test, flames were seen flashing through the footwell and underside of the dashboard. From the post-fire photograph shown in Figure 4.33, it is clear that high temperatures resulted in the footwell by the presence of charred and melted material. Unfortunately, the temperature data does not correlate to this observation. Flames were able to penetrate the firewall, though, perhaps indicating that the lack of insulation coverage played a role.

Figure 4.33. Post-fire damage to FR Material passenger footwell after flame penetration

- **Dashboard**

Current Material & FR Material Dashboard Temperatures
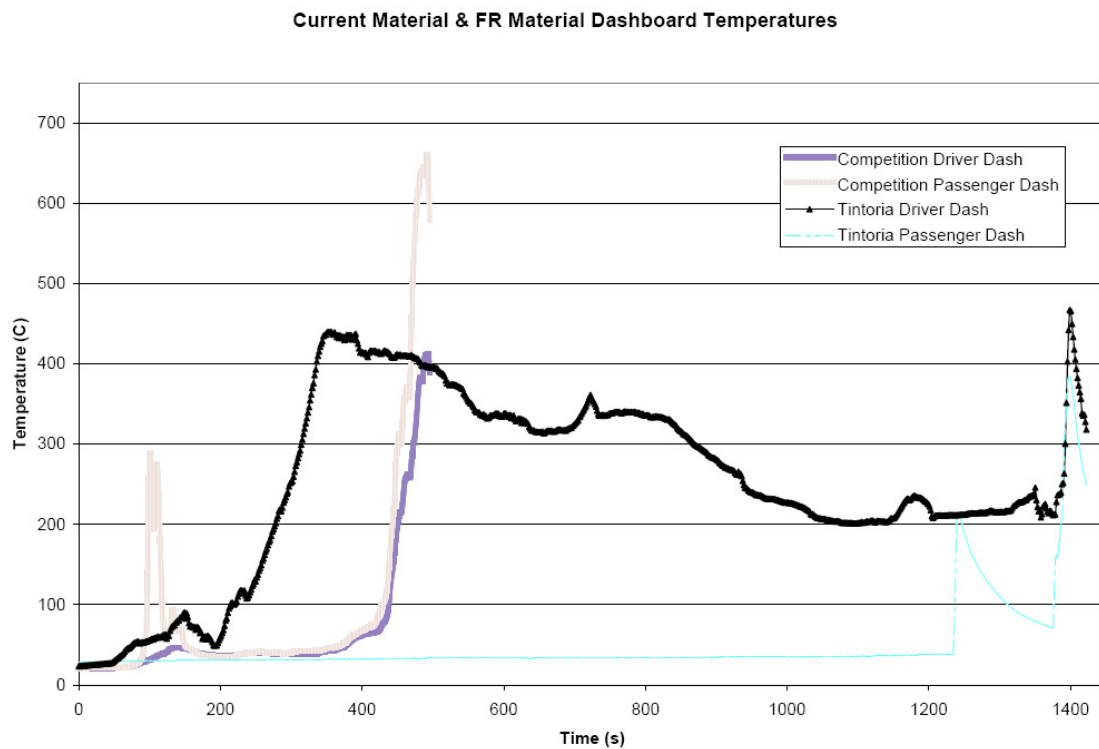
Figure 4.34. FR Material and Current Material Dashboard Temperatures

In Figure 4.34, the temperature profiles of the Current Material dashboard follow each other very closely. The spike of the passenger side thermocouple at 90 seconds could be indicative of the flames leaping around the door jam into the passenger compartment just under the windshield. Then as the engine fire becomes more involved, the windshield and the area just inside above the dashboard begin to heat up. This can be seen as the two plots follow the same path at 380 seconds and on. The windshield was cracked by this point, as shown in Figures 4.35 and 4.36, allowing even more heat into the region above the dashboard. Then at approximately 415 seconds, the passenger dashboard temperature begins its steeper rise than the driver side dashboard. This can be related to the open door allowing more heat to enter the vehicle by means of the passenger side. In the FR

Material test, the dashboard temperature begins its ascent at about 220 seconds, continuing until approximately 360 seconds where it begins a slow reduction in temperature for most of the rest of the test. The passenger dash registers little rise in temperature for most of the test until two spikes near the end of the test.

Figure 4.35. Cracked windshield on Current Material post-fire

Figure 4.36. Crack windshield interior view on Current Material post-fire

- **Occupant Seating Area**

Current Material & FR Material Seat Temperatures
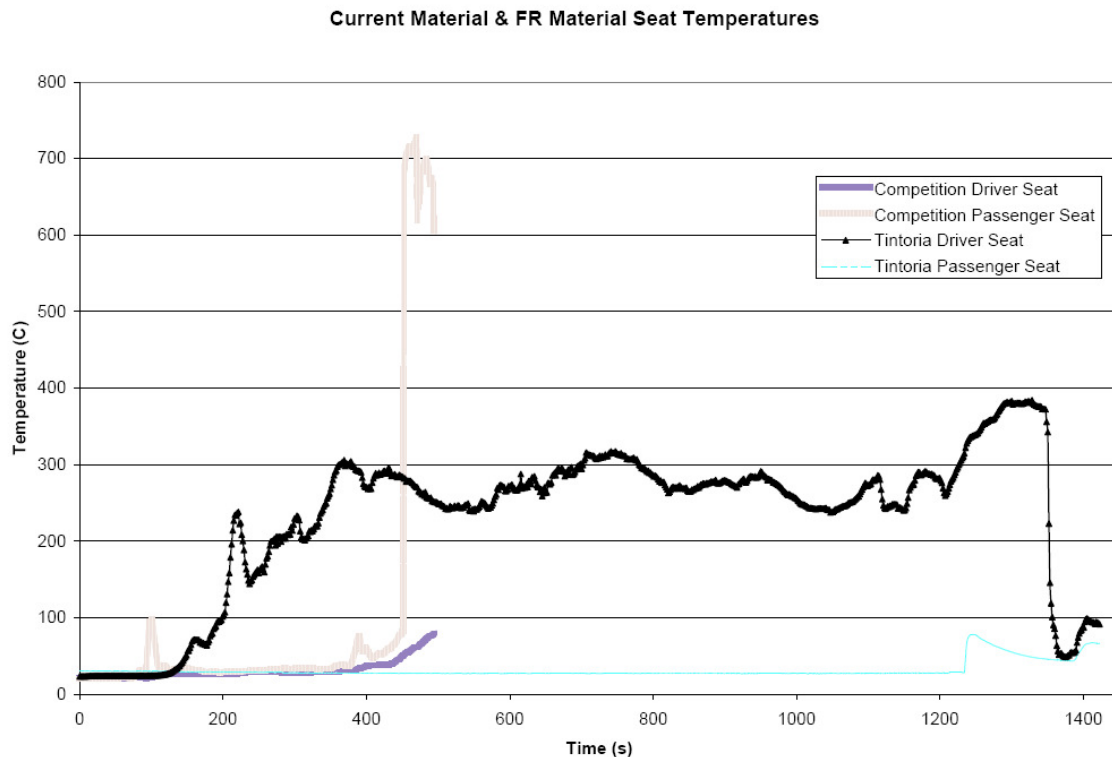
Figure 4.37. FR Material and Current Material Occupant Seating Area Temperatures

The readings in Figure 4.37 for the occupant seating areas are fairly similar for both tests for most time periods, other than the FR Material driver seat. A pattern observed in the FR Material tests is the high temperatures recorded on the driver side of the vehicle. An observer noticed that flames appeared to have flashed through the AC vent on the driver side; even if these flames only passed through once, it is still apparent that a large amount of heat must be traveling through penetrations in the dashboard. This could account for the high temperatures in the driver side dash and footwell, with peaks at about 450 C; the peak of the seat was only 310 C, which is reasonable because of its distance from the footwell and the dash. The Current Material peaks to 100 C at about 100 seconds, which can be associated with the flames entering through the door. The peak at 450 seconds matches the peaks in other graphs as well.

4.2.3.4 Large-scale Tests Results Discussion
Results from the two large-scale tests are inconclusive. With respect to the role of the

firewall insulation on the potential for fire spread through the firewall, the plots of the

temperature profiles in the four zones as well as the plots of the temperatures on the

passenger and driver side show that temperatures vary greatly dependent upon location in

the vehicle both in the medial direction and the lateral direction. Temperatures in the

engine compartment are higher than in the passenger compartment, but in some of the

test areas, temperatures across the passenger compartment varied greatly. This is due to

the impingement of flames and/or large heat fluxes through the firewall. Differences in

the dashboard arrangement on the passenger and driver side could cause these variances

as well as the increased mechanical components on the driver side. These graphs are not

meant to compare between the FR Material and Current Material tests on the basis of

time. The fire growth time is very dependent upon the packing of the Excelsior and

engine orientation, as well as the fact that "time of ignition" is subjective, such that

comparisons in time cannot be made.

In order to help explain the variations in the data, there are a few considerations to be

made. One is the lack of insulation throughout the dashboard. As mentioned before, the

insulation barely reached the top of the footwell carpeting, let alone continuing up behind

the dashboard. Considering that most of the heat that impinged upon the passenger

compartment came through the dashboard area and vents, the lack of insulation in those

areas could have made a difference.

The wind was also a large factor in the outcome of these tests. Because of the wind

speeds and the opposing car orientations, significant differences in the progression and

growth of the fire resulted. Although observations could not be made concerning how

the fire was progressing in the engine compartment, the wind undoubtedly pushed heat in

different directions for both tests, resulting in the variable engine compartment

temperatures seen in some of the readings. As the heat transfers from the engine

compartment to the passenger compartment, fluctuations in engine temperatures affect

the interior temperatures as well.

4.2.4 Experimental Results Discussion

The results of the large scale tests were inconclusive in terms of the importance of the

firewall insulation as a method of preventing flame and heat spread. From the previous

small-scale and bench-scale tests, it is evident that the FR Material material has better

insulating qualities and a much lower flame spread rate, but these advantages on the

small scale were not apparent in the large scale tests.

The ignition properties of the FR Material insulation are not adequate in light of the

stipulations of NFPA 556. The document states that all materials used in ductwork

should have times to ignition no lower than 90 seconds when tested at an incident heat

flux of 25 kW/m^2 in the cone calorimeter in the horizontal position [1]. Although the

document is referring to the plastics used in the actual ductwork, the insulation should not

be overlooked in terms of its limited resistance to ignition at incident heat fluxes because

of its location adjacent to ductwork and the dashboard. If the insulation is installed

further behind the dashboard area and if ignited, it becomes a hazard for the materials surrounding it. From the results of the bench-scale tests, the time to ignition of the FR Material insulation at an incident heat flux of 25 kW/m^2 is less than 10 seconds.

The FR Material insulation meets and exceeds the other parameters set by NFPA 556. The document states that the average heat release rate of the sample must be no more than 80 kW/m^2, from ignition to the completion of three minutes, when tested in a cone calorimeter in the horizontal orientation at an incident heat flux of 25 kW/m^2 [1]; the MVFRI study suggests a maximum heat release rate of 100 kW/m^2. At 25 kW/m^2, the highest HRR of the FR Material insulation was 41.3 kW/m^2. Additionally, even at an incident heat flux of 50 kW/m^2, the highest HRR was 54.8 kW/m^2. The FR Material insulation shows excellent performance in the HRR criteria and thus is a lower hazard to surrounding materials than the current insulation.

The Current Material does not meet the flame spread, ignition, and heat release rate requirements of NFPA 556. The average heat release rate of the Current Material at an incident heat flux of 25 kW/m^2 was 88.4 kW/m^2, which is greater than the requirement of 80 kW/m^2 stipulated by NFPA 556. The Current Material's ignition properties under ambient conditions as well as at an incident heat flux do not pass the requirements of NFPA 556; the Current Material suffers the same shortcomings as the FR material. Flame spread in the Current Material is too quick in both the horizontal and vertical positions to pass the requirements of NFPA 556.

NFPA 556 also states that materials must also not produce flaming drips when exposed to heat and flame [1]. In the small scale tests, the FR Material product was highly resistant to both ignition and flaming drips in both the horizontal and vertical positions. The Current Material samples did in fact produce flaming deposits; the FR Material insulation is an improvement upon the current insulation.

4.3 Cost-Benefit Results

After the parametric analysis, the percent reductions in deaths and property loss that equalize benefits and costs were found. The results are shown in Table 4.5 as calculated from the methods outlined in Section 3.2; these results are independent of one another. The percentages for deaths and property loss are if only one benefit is considered in equalizing benefits and costs.

Installed Cost	Percent Reduction Necessary To Meet Installed Costs	
	Death	**Property Loss**
$5	13.0%	17.4%
$6	15.6%	20.9%
$7	18.2%	24.3%
$8	20.8%	27.8%
$9	23.4%	31.3%
$10	26.0%	34.7%

Table 4.5. Cost-Benefit Results FR Material Insulation

These results indicate that at the minimum installed cost of $5, a 13.0% reduction in deaths and a 17.4% reduction in property loss would need to be achieved in order to meet the total installed cost. At the maximum installed cost of $10, a 26.0% reduction in deaths and a 34.7% reduction in property loss would need to be achieved in order to meet

the total installed cost. A plot of these values with linear trendlines is shown in Figure

4.38.

Independent Percentage Lives Saved and Property Loss Prevented versus Installed Cost for Break-Even Scenario
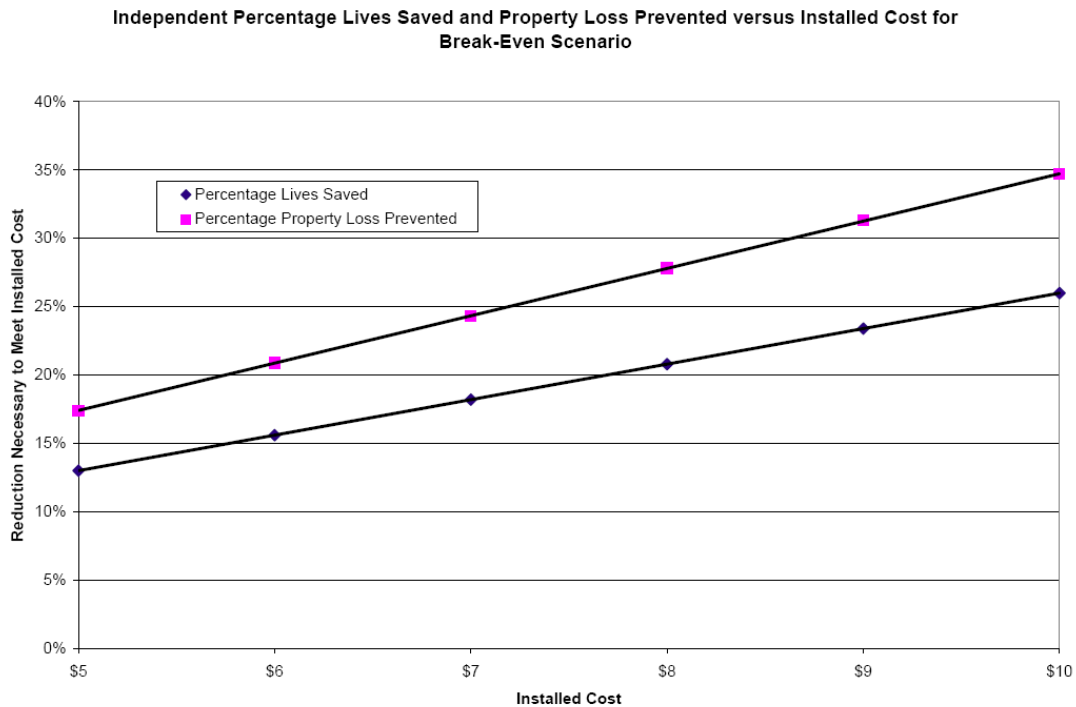
Figure 4.38. Independent Property Loss and Death Reduction Percentages versus Installed Cost

This data is incomplete, though, because in vehicle fires both property and lives will be

saved by the installation of the FR Material. In order to determine what combinations of

percentages equalize the benefits and costs, the maximum reduction percentage in deaths

for a particular installed cost was plotted against 0.0% property loss and vice versa for the

maximum reduction percentage in property loss. This was performed for each installed

cost and the results are shown in Figure 4.39.
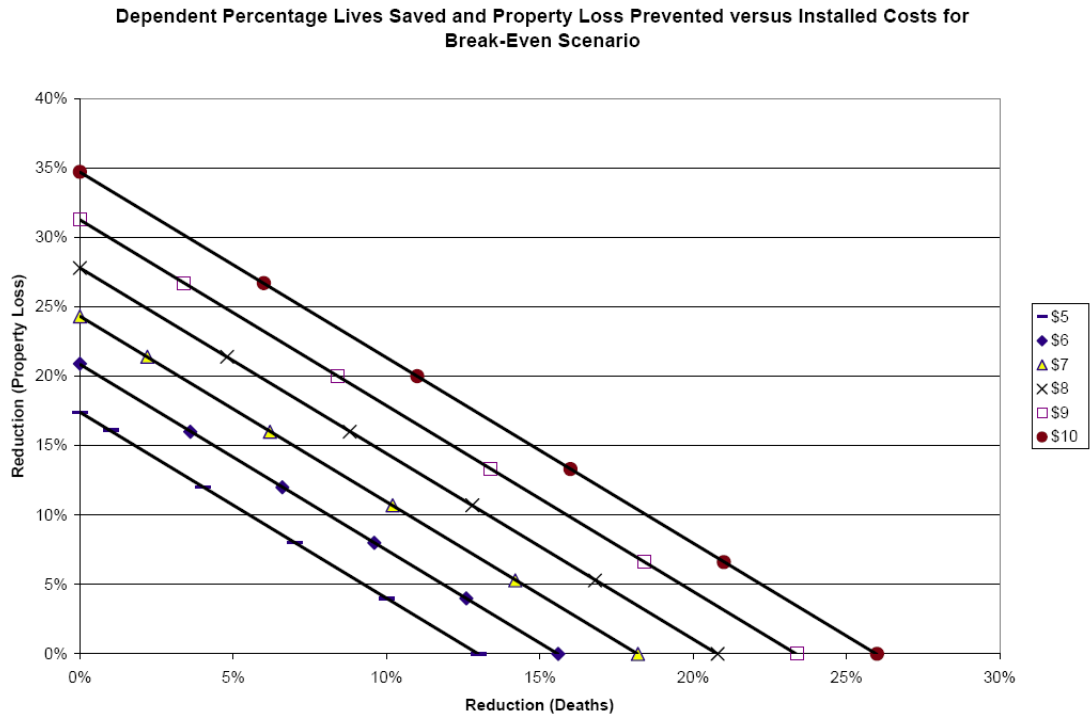
Figure 4.39. Dependent Property Loss and Death Reduction Percentages versus Installed Cost

From Figure 4.39, each trendline gives coordinating percent reduction values for both

benefits in order to equalize benefits and costs. This provides an opportunity to examine

the feasibility of each installed cost and the possible reduction percentages that can apply.

Based on this data, an installed cost of $5 per car would require the least reduction in

property loss and deaths, but the $5 install cost is the bare minimum cost and a more

realistic cost should be selected. Although the FR Material manufacturer stated that an

installation cost of $5.00 is possible for some vehicles, not every vehicle will fall into this

cost. The $8 cost was selected under the assumption that it best represents the average

cost of installation; this was assumed because of the trends of larger car use in the U.S.

currently. At $8, the plot requires that at 11% reduction in deaths, a 13.1% reduction in

property loss is necessary to equalize benefits and costs. These values will be considered

in the final analysis of the FR Material.

4.4 Discussion of Concerns with Research and Technology

Based on the material presented in Section 2.2.1 and the results of the experimental and cost-benefit analysis, no single material improvement will eliminate the hazards of vehicle fires. If many of the materials utilized are required to meet a stringent standard, their cumulative effect may have significant, positive result in reducing the fire hazard. But the improvement of these materials alone may not the answer to the vehicle fire problem. Better materials may be able to prevent the propagation of flames and heat, but they will not always prevent the fire from igniting and causing its intrinsic damage in the area of origin. Technology must be applied that can stop the fire from igniting or suppress it quickly if ignition occurs. In this sense, the fire resistant materials act as redundant fire protection.

This redundancy is critical, as Leland Shields stated his concerns with maintenance issues and reliability of suppression systems at the Workshop on Fire Suppression Needs. Very little dynamic testing has been conducted to test the integrity of complex suppression systems in the event of an accident. With so many unpredictable scenarios that could occur as a result of a crash, there are chances that a suppression system may not activate or could in fact activate prematurely; there are possibilities for issues of visibility, toxicity, and service injuries to occur. A more in depth analysis of field collision data could provide better information concerning events that lead to fire but could also damage a suppression system in place [11].

Unfortunately, these joint systems of both active suppression systems and passive protection systems are victim to their cost-effectiveness. As previously stated, no single

system or material can end the vehicle fire problem, so an amalgam of technologies is required; these technologies require high costs with seemingly low returns. Consumers and manufacturers are slow to see the benefits of expensive safety measures. Though vehicle fire deaths may be a statistically frightening issue on paper, there is very little concern among the public for an issue so seldomly on their minds. Bennett compared the vehicle fire safety situation to the evolution of air bags decades ago and the struggle to get the public to pay for advanced safety features [11]. A market study to determine how much the public is concerned with and how much they are willing to pay for vehicle fire safety would provide a wealth of information on how to move forward in this process. Based on this information, public education and awareness through government publications could be disseminated in an effective manner.

Just as with most other technologies, the initial costs will be undoubtedly expensive. Paul Wirenga of Aerojet discussed his experience in "…military systems and how preliminary technology developments progress in fits and starts, initially costly, but more economical with time as engineering optimization has time to mature." Because of this initial growth period of technologies, the only groups who might be willing to take the risk are those with histories of breaking new ground and who possess the capital necessary to accept such risks. This would lead only a select few manufacturers to initially provide the technologies; from other safety technologies introduced in the past, it is normally high-end automotive manufacturers that help to build the momentum. Once the technologies are proven, prices should lower and the technologies can be made available to the mainstream public.

While these manufacturers normally take the lead in emerging automotive technologies, there is the possibility that they still will not see that the benefits of investing in this technology outweigh the costs. Steve Hodges from Kidde noted that automobile manufacturers may look at the grand scheme of losses due to their product, in which fire related losses represent only a small fraction of total collision-related losses [11]. Then again, perhaps the vehicle fire problem is not viewed in the proper perspective. Although the losses associated with vehicle fires have already been outlined, there remain consequences due to vehicle fires outside the realm already considered.

So far in research, almost all effort has been put forth into studying collision-related situations. These situations may be the most detrimental in terms of losses but losses still occur in non-crash fires. Engines overheat, wires wear through, and flammable liquids leak; these are all examples of non-collision fire hazards. Most importantly, these fires may in fact be the simplest to prevent/suppress because no deformation has resulted from a crash which reduces travel paths for flames, maintains fuel tank integrity, and poses no inoperability issues with a suppression system. The occurrence of emergency response will be reduced, saving tax money and the chance of emergency response personnel injuries or death. The location of vehicle fires is critical as well; spalling on highways can occur, incurring additional road service costs. Additionally, if the car is located under a bridge or tunnel, extensive damage can occur to the structure as well as to surrounding vehicles and individuals. Fires produce environmental damages and costs as well, such as toxic air pollutants and runoff and the threat of forest fires [11].

All these factors must be taken into consideration when approaching the vehicle fire

problem, but the research that has already been conducted and the work that the NFPA

has put into NFPA 556 are an excellent foundation for development.

Chapter 5: Summary and Conclusions

The technology and expertise exists to provide the public with better vehicle fire protection. The first steps in providing progress should be the research and development of new and existing fire protection technologies and materials and the application of a well-planned, scientifically based standard which regulates those materials and technologies for vehicles. The National Fire Protection Association has made excellent progress along this avenue of a standard with the creation of NFPA 556. It stands to regulate the materials that are used in motor vehicles and provide a well defined and stringent baseline standard through which all vehicle components could be filtered.

Based on these regulations put forth by NFPA 556, this project has evaluated the potential costs and benefits associated with the replacement of the current acoustical insulation material used in vehicles with a more fire retardant material. Upon reviewing the experimental and cost-benefit analysis results for the FR Material product, it has been concluded that additional improvements must be made for its use in motor vehicles. Although this material is superior to the current insulation in its heat release rate, insulative qualities, burning characteristics, and resistance to flame spread, all of which pass the requirements of NFPA 556, its propensity for ignition does not pass the requirements of NFPA 556. Additionally, based on the results of the cost-benefit analysis, a $8 installed cost would require an 11.0% reduction in deaths and a 13.1% reduction in property loss to justify the costs and benefits. The experimental results are inconclusive. They do not provide adequate results that can be used determine whether or not the FR Material could produce the calculated reductions. Due to the FR Material

insulation's inability to resist ignition at relatively low incident heat fluxes (a stipulation of NFPA 556) combined with its installation cost, the author cannot justify the replacement of the current insulation product. The improvement in low incident heat flux ignition resistance as well as the material's performance in HRR should not be overlooked. The FR Material is an improvement over the baseline material and further product testing should be conducted to improve its ignition qualities at higher incident heat fluxes.

The application of the requirements of NFPA 556 in this research is a key example of why a more encompassing and stringent set of standards is necessary to reduce the hazards of vehicle fires. The Current Material, though having passed the flame spread requirements of FMVSS 302 some time ago, exhibited few other qualities necessary to protect vehicles and occupants from fire. Even the new and safer FR Material was unable to meet the ignition requirements of NFPA 556; despite its exemplary performance in other requirements, its ignition performance did not qualify the FR material as an NFPA 556 approved material. Even if the FR Material had passed the requirements, the results from the bench-scale and large-scale tests created doubts as to whether the insulation alone can realistically reduce deaths and property loss. No one material will drastically alter the current vehicle fire trends but if such a strict standard is able to improve the fire resistance of all materials, the cumulative effect will be evident.

Research and development into fire suppression and prevention technologies has been conducted but vehicle fires present an unusual and dynamic challenge for fire protection;

wear and tear, collisions, and the large variations in vehicle design are all issues to be considered by researchers. From technologies research to product testing and evaluation under more stringent standards such as NFPA 556, all input will assist in the resolution of the vehicle fire problem. Vehicle fire safety has progressed so little in the last three decades, while science and technology has progressed so greatly, that the gap for development is realistically surmountable. Though there are many hurdles to overcome in tackling the vehicle fire problem, including political, financial, and technical challenges, the initial steps must be taken in order to begin the education and awareness process. The basis of research and development already exists, it only needs to be built upon and expanded. NFPA 556 does an excellent job of setting the bar for future improvements in the industry and the testing of automotive materials and components.

References

[1] National Fire Protection Association. *NFPA 556, Fire Prevention Code,* 2007 Draft ed. *Q*uincy, MA.: National Fire Protection Association, 2007.

[2] Tewarson, A., Quintiere, J., and Purser, D., "Fire Behavior of Materials in Vehicle Crash Fires and Survivability of the Passengers", Technical Report 2005-01-1555, prepared by FM Global, Norwood, MA for MVFRI, Charlottesville, VA 2005.

[3] Hamins, A., "Vehicle Fire Suppression Needs", NISTIR 7406, prepared by NIST, Gaithersburg, MD for MVFRI, Charlottesville, VA March 2007.

[4] Tewarson, A., Quintiere, J., and Purser, D., "Improving Survivability in Motor Vehicle Fires", Interflam 2007. International Interflam Conference, 11th Proceedings. Volume 1. September 3-5, 2007, London, England, 135-143 pp, (2007).

[5] M. Spearpoint, S.M. Lownick, J.L. Torero, and T. Steinhaus, "Ignition Performance of New and Used Motor Vehicle Uphlstery Fabrics," Fire and Materials, 29, 265-282 (2005).

[6] National Safety Council: NSC.org "Estimating the Costs of Unintentional Injuries, 2006" <http://www.nsc.org/resources/issues/estcost.aspx>. 2007.

[7] Tessmer, Joseph. "An Analysis of Fires in Passenger Cars, Light Trucks, and Vans", NHSTA Technical Report DOT HS 808 208, U.S. Department of Transportation, National Highway Traffic Safety Administration, Dec 1994.

[8] Tewarson, A., Quintiere, J., and Purser, D., "Post Collision Motor Vehicle Fires", Technical Report 0003018009, prepared for MVFRI, Charlottesville, VA Oct 2005.

[9] Santrock, Jeffrey. "Evaluation of Motor Vehicle Fire Initiation and Propagation Part 13", NHSTA 98 3588 203, Prepared by General Motors for the U.S. Department of Transportation, National Highway Traffic Safety Administration.

[10] U.S.F.A., "Highway Vehicle Fires," Topical Fire Research Series, Vol. 2, No. 4, U.S Fire Administration, March 2002.

[11] Bahouth, George. "Analysis of Data Systems to Assess Possibilities for Evaluating Egress and Fire Penetration Times", Interim Report prepared for MVFRI, Oct 2004.

[12] "Traffic Safety Facts", Fatal Analysis Reporting System (FARS), US Department of Transportation, National Highway Traffic Safety Administration, Washington, DC, 1994, 1995, 1996, 1998, 1999, 2000, 2001.

[13] Cyphers, D.C., Frederick, S.A., Haas, J.P., *Enhanced Powder Panels,* Proceedings of HOTWC-2002 12th Halon Options Technical Working Conference, Albuquerque, NM, April 20 – May 2, 2002 (R.G. Gann and P.A. Reneke, Eds.) NIST Special Pub. 984, June 2002.

[14] A. Goldsmith, "Flammability Characteristics of Vehicle Interior Materials," Final Technical Report, J6152, Illinois Institute of Technology Research Institute, Chicago (1969).

[15] Committee on Fire Safety Aspects of Polymeric Materials, "Fire Safety Aspects of Polymeric Materials, Volume 8, Land Transportation Vehicles," National Materials Advisory Board, National Academy of Sciences, Publication NMAB 318-8, Washington, D.C., pp. 158, 1979.

[16] A. Tewarson, "A Study of the Flammability of Plastics in Vehicle Components and

Parts, Technical Report FMRC J.I. 0B1R7, Factory Mutual Research Corporation, Norwood, MA, October 1997.

[17] F.E.M.A., "Motor Vehicle Fires: What You Need to Know." Federal Emergency Management Agency, U.S. Fire Administration, FA-243, April 2003.

[18] Briggs, Peter and Hunter, John. "Pyromms: Macro Scale Multi-Component Materials in Fire", Report MMS16/014v6 prepared for Department of Trade and Industry, May 2004.

[19] Federal Motor Vehicle Safety Standard (FMVSS), Part 571.302: Flammability of Interior Materials, Code of Federal Regulations (CFR), Volume 49, Chapter V, October 1, 2003.

[20] California Department of Transportation. "Benefit-Cost Analysis", <http://www.dot.ca.gov> 2007. May 1 2008.

[21] Environmental Protection Agency. "Valuation of Human Life", <http://www.epa.gov/>, 2008. May 15 2008.

[22] Office of Highway Policy Information, "Highway Statistics 2006 Section III: Driver Licensing" U.S. Department of Transportation, Federal Highway Administration, 2007. May 15 2008.

[23] Consumer Price Indexes, U.S. Department of Labor, Bureau of Labor Statistics. <http://www.bls.gov/CPI/> 2007. May 15 2008.