NITROGEN FIRE SUPPRESSION SYSTEM FOR AUTOMOBILE UNDER-HOOD POST-COLLISION FIRE PROTECTION

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FINAL REPORT

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FOREWARD

This final report is also the Master Thesis of Mr. John Gunderson defended on Thursday, August 11, 2004. Dr. M. di Marzo directed the research leading to this thesis and the two readers were Drs. A. Marshall and F Mowrer of the Fire Protection Engineering Department – University of Maryland – College Park.

ABSTRACT

This thesis describes the development and testing of a Nitrogen Foam fire suppression system. The purpose of the system is to contain or extinguish fires that originate in the engine compartments of automobiles after front end collisions. The Nitrogen foam creates an inert environment within the engine compartment that is sustainable for a period of at least 10 minutes. Thus, the system is capable of extinguishing fires that have already started at the time of system activation and prevent fires from starting after the foam has been deployed.

Testing shows that at an expansion ratio of 220 the Nitrogen foam will fill all of the voids within an engine compartment without freely flowing down and out of the engine compartment. Full scale burn tests show that the system is capable of containing and extinguishing fires that originate within the engine compartment at the location of the battery.

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1 - INTRODUCTION

1.1 Problem Statement

This thesis describes the development and testing of a novel approach to protecting automobiles from fires that originate within the engine compartment after a collision. The concept is to use Nitrogen foam to extinguish fires that are ignited simultaneously with the collision and to protect the engine compartment from ignition by sources, such as electrical shorts, that could cause ignition some time after the collision for a period of time long enough to allow the intervention of fire department personnel.

Nitrogen is considered, as the gaseous agent, because it poses no environmental concern, is readily available and prevents ignition and combustion at molar fractions in excess of 86%. The fire protection foam serves to keep the Nitrogen within the engine compartment, thus preserving the inert environment past the initial application. The foam also participates in the fire protection process by smothering flames and cooling hot components.

This thesis describes the development of the Nitrogen foam fire suppression apparatus from the initial concept, through the development process and initial testing, and finishes with an in-depth description of the performance of the apparatus in a number of full-scale, post-collision fire scenarios.

1.2 Review of the Literature

Some of the relevant investigations conducted at NIST and GMC on under-hood post-crash fires are listed in the NHTSA docket number 3588 of 1998. Of this extensive list the following documents provided information useful for our study:

NHTSA-98-3588-132

Evaluation of active suppression in simulated post-collision vehicle fires by A. Hamins

Of all the documents from NHTSA docket 98-3588, this report from NIST has prominent relevance to this project. The others provide some supporting information in the conduct and characterization of testing procedures. This report outlines four important elements:

1. Fire scenario definition
2. Vehicle geometry characterization
3. Suppression agent and suppression system characterization
4. Nitrogen performance

The report presents a comprehensive evaluation of the performance of fire suppression agents in vehicle post-crash scenarios. The two scenarios considered are: a) engine compartment fire and b) pool fire under the vehicle. Of these two scenarios the engine compartment fire was selected for this project.

The report provides important information for the development of the apparatus and the test scenarios used. The following areas of interest have been identified: a) fire scenario definition; b) vehicle geometry characterization; c) suppression agent and suppression system characterization and d) Nitrogen performance. In the following, each of these areas will be discussed.

<u>Fire scenario definition:</u> The report describes a variety of tests initiated with fuel spills and leaks. The fuel is introduced near the front panel or near the top panel in the engine compartment. During testing, fires will be initiated near the front of the engine compartment in the proximity of the battery. This location is similar to the locations

selected in the report. Further, it is postulated that the Nitrogen foam system will activate at impact. Therefore, the fire growth is limited by the foam deployment to less than one minute. In order to maximize this time, the foam generator will be placed at the farthest possible location from the fire source consistent with optimal deployment strategies based on the engine geometry.

Vehicle geometry characterization: The NIST report examines a broad spectrum of engine compartment dimensions for several classes of vehicles. The strategy during this project will be too inert the top portion of the engine compartment. Therefore, the typical volumes of Nitrogen foam required for the various classes of vehicles are evaluated based on an average of 380 L. The initial design of the foam generator is based on achieving a foam volume of about 50% of the engine compartment volume or about 200 L. This design parameter is based on cup burn data requiring about 30% of the compartment volume for Nitrogen to achieve suppression. With the proposed aqueous foaming agent, the manufacturer recommends an expansion ratio of 50. This would imply a volume of solution of about 4 L. The optimal expansion ratio and Nitrogen foam volume are determined as part of this project.

Suppression agent and suppression system characterization: The discussion provided in section 1.3.1 of the NIST report provides nine elements that can be used to characterize a suppressant and a suppressant deployment system. These key elements are listed as:

a) vulnerability
b) false discharge
c) environmental impact
d) required agent mass
e) re-ignition performance
f) suppression effectiveness
g) maintenance requirements

h) toxicity

i) cost

These nine elements are discussed at the conclusion of this thesis in Section 5.2 and illustrate the potential of the Nitrogen foam concept in comparison with the suppression strategies examined in the NIST report.

Nitrogen performance: A significant portion of the report is devoted to the analysis of Nitrogen performance. This extensive experimental data will provide significant guidance in the performance of the present study. Issues related to the Nitrogen foam deployment throughout the top portion of the engine compartment are significant to the Nitrogen foam deployment strategy.

The effect of hood deformation during the crash and the presence of surface openings is carefully considered in evaluating the performance of the foaming product proposed and may result in the alternate selection of high expansion foam products. The report shows some interesting trends for gaseous Nitrogen in reference to this issue.

Delivery rate is also important as previously noted in reference to the fire growth. Further, secondary in-situ deployment of the Nitrogen as the foam degrades is also important and must be carefully evaluated. This last issue is a key element of the Nitrogen foam proposed suppression concept.

NHTSA-98-3588-38

Evaluation of motor vehicle fire initiation and propagation, vehicle crash and fire propagation test program by Jack L. Jensen and Jeffrey Santrock, GMC

This document describes a comprehensive testing procedure for post-crash vehicle fires. The conditions of the various components and fluid characteristics are considered in detail.

The possible ignition scenarios for the engine compartment include solid fuels heated by electrical shorts, liquid fuels sprayed on to hot surfaces and gasoline leaks ignited by electrical arcs. Additionally, the gasoline spilled from the tank is also considered as a fire ignition scenario. Organic polymers are considered as additional flammable elements in the development of the car fire.

The vehicle conditions at the initiation of the fire test are described and the entire vehicle including the engine compartment is kept at ambient temperature initially. This is an important element for the present investigation. Also relevant to the present program is the description of the instrumentation used in the tests.

The reference list includes a paper from the Fire Safety Journal on the characterization of the fire behavior of a burning car. This document is discussed next.

Fire Safety Journal 23 (1994) 17-35, Characterization of the fire behavior of burning passenger car. Part I: car fire Experiments by J. Mangs, O. Keski-Rahkonen

This document is cited in *NHTSA-98-3588-38*. The paper provides significant details concerning the development of fire in the engine compartment of cars. The first important conclusion is that the fire transitions from the engine compartment to the passenger compartment within 4 to 5 minutes. Increased levels of CO and CO_2 are observed at earlier times. This information bounds the timeframe of the suppression process. If the fire originates in the engine compartment, it must be extinguished vary rapidly. The fire must be suppressed in 1 to 2 minutes to ensure that the passenger cabin remains tenable. The first possible scenario is a fast deployment of the agent at the time of the crash that quickly overwhelms the fire in its early growth stage. Note that the data indicates that the fire growth is extremely fast and once the fire has become large it is too late to intervene. Therefore, the fires that are considered in the present study will be small. The second conclusion we can draw is that once the agent is completely deployed, one has to assess its resistance to a pool fire under the engine compartment that develops later in the accident. This second aspect, while not the main goal of this project, is investigated during testing.

The paper provides important information on the placement of instrumentation within the vehicle and details the testing procedures using small Gasoline pool fires as fire sources.

1.3 Thesis Organization

The remainder of the thesis is organized as follows. Chapter 2 describes the foam generator design process and initial testing. Chapter 3 outlines the collision scenarios that are considered and identifies the tests to be carried out during the full scale burn testing phase. Chapter 4 provides a description of the full scale burn tests carried out to test the performance of the foam generator in actual automobile fire scenarios. Chapter 5 provides a summary and discussion of the results derived from the full scale burn test data, a list of the relevant conclusions and outlines possible future work.

2 – DESIGN AND INITIAL TESTING OF FOAM GENERATOR

2.1 Foam Generator Design

2.1.1 Overall Concept

In the event of a situation that could lead to a fire within the engine compartment of an automobile it is desirable to create an inert environment under the hood. This could prevent the fire from starting or, if the fire has already started, extinguish it or keep it from spreading into the passenger cabin of the automobile until the occupants can be removed.

There are many openings present in the engine compartment of an automobile available for a gas to escape if the gas is injected directly under the hood. We intend to encapsulate the inert gas in fire protection foam. The purpose of the foam is to carry the inert gas throughout the under hood area without letting it escape. When the foam encounters hot spots or areas on fire the foam will release the inert gas in that localized area and eliminate or confine the threat. Additionally, the foam itself will help to smother flames and cool hot components.

During testing, two different aqueous foams are used. The first is manufactured by ANSUL and identified as Ansulite 3x3. This foam was used during the development stage of the project. The second is manufactured by CHEMGUARD Inc. and identified as Ecoguard 3% F3. This foam was used during most of the burn testing.

The optimal foam is capable of flowing throughout the engine compartment, penetrating into all of the available openings while at the same time being able to remain in those openings and not flow down and out of the engine compartment. Secondarily, it would be desirable for the foam to be durable enough to stand up to elevated temperatures without breaking down too quickly so that a level of protection within the engine compartment does not diminish too quickly. However, the ability of the foam to stay within the engine compartment should not be compromised in order to prevent breakdown.

A foam generator with the desirable characteristics is not available, so a novel foam generator able to produce the Nitrogen foam is developed. The basic premise for the design of the foam generator is based on a large-scale, blower-type foam generator [Bryan, 1993]. In these systems a fan pushes air through a short pipe of about the same length as the diameter of the fan. A metal screen covers the end of the pipe. A nozzle positioned in the middle of the pipe and pointed at the screen injects the foam solution. The foam solution coats the screen meshes and is blown out by the air thus creating foam.

These foam generator systems are up to a meter across and produce large volumes of high expansion foam. In order for the system to fit within the engine compartment the system for under the hood of an automobile should only be five to ten centimeters across and produce about 200 to 400 L/min of foam. Instead of using air the system will use Nitrogen gas. The system should be able to produce foam with an expansion ratio of 100 to 300, with an initial goal of 200. The expansion ratio is the ratio of the foam volume to the volume of the initial liquid solution.

The foam generating system consists of two tanks connected by a piping system to the foam generator (see Figure 1). One of the tanks holds the pressurized Nitrogen gas. The other is filled with the foam solution. The Nitrogen gas is used to pressurize the entire system. A regulator attached to the Nitrogen tank controls the pressure of the entire system (see Figure 2). The Nitrogen and the foam solution do not mix until they reach the foam generator. Once at the foam generator the Nitrogen and the foam solution are injected at controlled rates into a mixing chamber where they mix and create the foam. See Figures 3 and 4.

2.1.2 Nitrogen System

The Nitrogen system controls the pressure and flow for the entire system. High-pressure industrial Nitrogen gas is used. The Nitrogen pressure is set between 0 to 680 kPa (100 psig) by a pressure regulator. As the Nitrogen flows out of the regulator it encounters two cross-junctions (see Figure 5). At the upper cross-junction there is a pressure relief valve set to 100 psi that protects the system and a valve for venting. At the lower cross-junction the Nitrogen flows into the foam solution tank and pressurizes it. An additional valve on this junction allows the Nitrogen to flow into a long piece of high pressure, rubber tubing that is directly connected to the foam generator. A block valve is placed downstream of the pressure regulator to isolate the system from the Nitrogen tank.

2.1.3 Solution System

The solution tank is a 10 Liter steel tank with connection points at the top and bottom and two connections at either end of the tank on the sides (see Figure 6). A level gauge is connected to the two side connections to monitor the solution level within the tank. The connection at the top is used to pressurize the system. The bottom connection leads to a ‘T’ junction. On one side of the ‘T’ is a valve that is used to fill/drain the tank. The other side of the ‘T’ connects to a needle flow control valve. The valve is connected to the foam generator via a length of clear plastic tubing. There is also a pressure gauge right after the flow control valve so that the pressure in the solution line can be monitored.

2.1.4 Foam Generator

The foam generator is a block of aluminum 50 x 90 x 120 mm (see Figure 7). A circular area, 64 mm in diameter, is hollowed out of the middle of the block. It has a depth of 38 mm. Then the circular area decreases in diameter by 3 mm and continues to a total depth of 51 mm (see Figure 8). A piece of 64 mm diameter pipe fits the circular area and sits on the ledge [see Figure 10]. The pipe diameter of 64 mm is based upon an initial desired foam flow rate of 200 L/min and a foam delivery rate of 1 m/s out of the pipe. Initially, the nozzle pipe being used is made of clear plastic. This allows for the observation of the behavior of the foam solution while it is inside of the nozzle pipe. The plastic pipe is also easier to cut and allows us to more easily experiment with nozzle pipes of different lengths.

There is a hole drilled through the block that is centered at the bottom of the circular hole. On the outside of the block there is a ½-inch threaded connection for the solution line. On the inside of the block is a ¼-inch threaded connection for a spray nozzle. Two different sized spray nozzles were used during testing. Both are manufactured by BETE and identified as WL ¼ and WL ½. The delivery characteristics for these two nozzles are shown in TABLE 1 and TABLE 2.

TABLE 1 – BETE WL ¼ Spray Nozzle Delivery Characteristics [BETE, Manual No. 104.3]]

Flow Rate (L/s)					
138 kPa	**204 kPa**	**272 kPa**	**408 kPa**	**544 kPa**	**680 kPa**
.0114	.0139	.0158	.0189	.0221	0.0240

TABLE 2 – BETE WL ½ Spray Nozzle Delivery Characteristics [BETE, Manual No. 104.3]]

Flow Rate (L/s)

138 kPa	204 kPa	272 kPa	408 kPa	544 kPa	680 kPa
.0228	.0278	0.0316	.0378	.0442	.0480

A small hole is drilled into the side of the block using a 3/32-inch drill bit, which gives an initial diameter of 2.3 mm. The hole connects tangentially with the bottom of the lower, hollowed out circular area on the inside of the block [see Figure 8]. On the outside of the block is a ½ inch threaded connection for the Nitrogen gas line to connect with [see Figure 7]. The Nitrogen gas enters the foam generator tangentially and forms a vortex around the solution spray nozzle. The small hole is characterized as an isentropic nozzle.

2.2 Foam Generator Performance

2.2.1 Nitrogen Flow

The initial stated goal is to produce 200 L/min of foam. Since the foam is made up primarily of Nitrogen it can be assumed that the flow rate of Nitrogen into the foam generator should be 200 L/min for calculation purposes. The 2.3 mm diameter nozzle controls the flow of Nitrogen into the foam generator. In order to change the flow rate of Nitrogen into the foam generator the overall pressure in the system is adjusted. In order to determine the mass rate of flow of an ideal gas through an isentropic nozzle the following relationship is used [Van Wylan, 1986].

$$\dot{G}=\frac{\dot{m}}{A}=\frac{P_o}{\sqrt{T_o}}\sqrt{\frac{k}{R}}\frac{1}{\left(\frac{k+1}{2}\right)^{\frac{k+1}{2(k-1)}}}$$

Where,

G = mass flow rate per area ($kg/s*m^2$)

m = mass flow rate (kg/s)

A = area of nozzle opening (m^2)

P_o = Operating pressure (Pa)

k = specific heat ratio = 1.4

R = gas constant = 297 J/kg*K

T_0 = Ambient (300 K)

A volumetric flow rate of 200 L/min yields a mass flow rate of 0.0038 kg/s. In the design we have an orifice of 2.3 mm in diameter or 4.1 mm^2 in area. Based on this area the mass flow rate at any pressure is determined using:

$$\dot{m} = P_{o,kPa} * (9.5 x 10^{-6}) \text{ ; (kg/s)}$$

An operating pressure of about 448 kPa (65 psi) will provide the desired Nitrogen flow rate. This operating pressure was kept constant and used throughout all of the testing.

The tubing leading up to the Nitrogen nozzle is sufficiently large so that there is minimal pressure loss when the gas is flowing. The tubing used is 13 mm diameter high pressure rubber tubing connected to 13 mm diameter stainless steel tubing.

The velocity of the Nitrogen in the line leading to the foam generator is calculated based on the inside area of the tubing and the flow rate. The inside area of the tubing is: 2700 mm^2. The flow rate is 200 L/min or 0.0033 m^3/s. The velocity inside the tubing is:

$$v = \frac{0.0033}{0.0127 x 10^{-3}} = 26.2 m/s$$

Some pressure will be lost as the Nitrogen travels to the foam generator. This will change the rate at which the Nitrogen is delivered to the foam generator. To calculate the pressure loss through the tube the Reynolds number and the friction factor must be calculated. The Reynolds number is defined as:

$$R=\frac{Lv}{\quad}$$

Where,

L = Length scale = inside diameter = 0.0127 m

v = Gas velocity = 26.2 m/s

ρ = Density of Nitrogen gas = 1.16 kg/m^3

μ = Dynamic viscosity = 17.6 x 10^{-6} N*s/m^2

Using these values the Reynolds number is calculated as: 2.19 x 10^4. The friction factor (f) is found using the Reynolds number and the Moody chart for pipe friction factor and is found to be: 0.030 [Finnemore, E.J; 2002].

The pressure losses through the tube are calculated using:

$$P= f\frac{L}{D}\frac{v^2}{2}$$

Where,

L = length of tube = 30 ft = 9.1 m

D = diameter of pipe = 0.0127 m

The tube is this long because during the full scale burn tests the Nitrogen gas and solution tanks need to be far away from the burning automobile so that the operator is not in any danger from the fire.

Using these values the pressure losses in the Nitrogen gas tubing are 8.6 kPa or 1.25 psi.

During testing, it was determined that the Nitrogen flow of 200 L/min was not sufficient. The flow of Nitrogen to the foam generator was increased, twice, by increasing the size of the Nitrogen orifice in the foam generator block. Table 4, at the end of Section 2.2.2 summarizes the effect the increased orifice size has on the mass flow rate equation and the pressure loss through the Nitrogen tube. The new values were calculated using the same methods shown above.

2.2.2 Solution Flow

The foam solution moves through the tubing system to the foam generator, pushed by the pressure head created by the Nitrogen. A needle flow control valve manufactured by Whitey and identified as B-ORF2 regulates the flow (see Figure 9). The flow of solution controls the flow rate out of the solution nozzle. Thus, by adjusting the control valve the expansion ratio can be changed. To achieve an expansion ratio of 200 the valve is operated at a Cv near 0.05. Cv is defined as:

$$Cv = \frac{GPM}{\sqrt{P_{psi}}}$$

Figure 10 shows the relationship between Cv and the number of turns that the valve is opened. The B-ORF2 needle flow control valve operates on the line labeled as 0.080" and provides fine control between Cv = 0 to 0.1.

The needle flow control valve connects to transparent plastic tubing, 9.5 mm in diameter. The tubing is transparent so that the liquid flow can be observed and any bubbles present during system priming can be eliminated. The plastic tubing connects to stainless steel tubing, 9.5 mm in diameter, which connects to the foam generator.

The solution is sprayed into the foam generator by a low flow, full cone spray nozzle. The nozzle characteristics are shown in Section 2.1.4.

As with the Nitrogen gas line, some pressure will be lost as the solution travels from the flow control valve to the spray nozzle. This pressure drop should be minimal since it is desirable for the pressure at the nozzle to be as close as possible to the pressure at the pressure gauge by the flow control valve. The larger the tubing that is used the lower the pressure drop will be. However, as the tubing size increases, the time to prime the tube with liquid will increase. Using the same method used to determine the pressure drop in the Nitrogen line, the expected pressure drops for 6.4 mm tubing, 9.5 mm tubing and 12.7 mm tubing were examined. For calculation purposes a solution flow of 3.8 L/min (1 gallon/min) is assumed. The actual flow will be lower. Table 3 shows the expected pressure drops and the expected time to prime the tube at an expansion ration of 200.

TABLE 3 – Pressure Loss and Time to Prime Solution Tube

Tube Size	6.4 mm	9.5 mm	12.7 mm
Pressure Loss	0.215 kPa	1.27 kPa	7.51 kPa
Time to Prime	18 sec.	41 sec	73 sec

Based on the faster fill time and minimal pressure losses the 9.5 mm tubing is selected. The difference between the pressure at the flow gauge and at the nozzle will be 1.27 kPa or 0.19 psig for a flow of 3.8 L/min. For lower flow rates the pressure loss will be lower.

As mentioned in Section 2.2.1, the initial Nitrogen flow rate of 200 L/min was found to be insufficient and was increased. In order to keep the expansion ratio the same the flow of solution was also increased. Table 4 summarizes the expected pressure loss at the spray nozzle for the new flows. The same 9.5 mm diameter tubing was used. The time to prime is not included because in practice the system was primed before use. The solution line was filled before any of the tests began so that foam would be produced as soon as the foam generator was turned on.

TABLE 4 – Nitrogen Mass Flow Rate, Nitrogen Line Pressure Loss and Solution Line Pressure Loss for Increased Flow Rates

Nitrogen Orifice Size	7/64”	1/8”
Nitrogen Mass Flow Rate Equation	$\dot{m} = P_{0,kPa} * (1.41 x 10^{-5})$; (kg/s)	$\dot{m} = P_{0,kPa} * (1.83 x 10^{-5})$; (kg/s)
New Nitrogen Flow Rate (at 448 kPa)	320 L/min	415 L/min
Nitrogen Line Pressure Loss	30.4 kPa (4.4 psi)	46.6 kPa (6.8 psi)
Solution Line Pressure Loss	2.1 kPa (0.3 psi)	3.4 kPa (0.5 psi)

2.2.3 Mesh Optimization

After the Nitrogen gas and the foam solution have exited their respective nozzles and entered into the nozzle pipe a series of meshes is needed to facilitate the mixing of the gas with the solution and the creation of foam with the desired expansion ratio.

The initial thought was that the majority of the gas would be moving in a vortex against the nozzle pipe walls, due to the tangential configuration of the gas injection, and that the foam solution should be injected into the chamber with a nozzle that would spray the majority of the solution onto the walls so that the gas and solution could start mixing. It was thought that the main mechanism for mixing between the Nitrogen and the solution would be through the turbulence caused by the high Nitrogen velocity. A layer of wire mesh screen placed over the end of the nozzle pipe would be completely wetted by the solution and then blown out creating the foam. There would be little pressure within the nozzle pipe and very low resistance for either the Nitrogen or the solution.

This configuration was tested with nozzle pipe lengths of eight and twelve inches and with various thickness of mesh over the end of the nozzle pipe. When these configurations were tested it was found that the Nitrogen did not mix very well with the solution and that the majority of the gas was just blowing out the end of the tube without picking up any of the solution along the way. The mesh was not being completely wetted thus leaving easy paths for the gas to escape. The foam that was being produced had a very high expansion ratio and was very wet (there was a lot of liquid passing through the screen unmixed).

This high throughput, low-pressure set-up did not facilitate the mixing of the Nitrogen and the solution. Based on this it was determined that a high pressure, high resistance set-up should be tried.

In order to increase the pressure and resistance in the nozzle pipe a 50 mm thick piece of steel wool was inserted into the pipe. The steel wool was supposed to become saturated with the foam solution and when the gas tried to find a path through the steel wool it would be forced to mix with the solution. A new spray nozzle was used that produced a full cone so that the steel wool could be completely wetted. A layer of wire mesh was put over the opening of the pipe in order to hold the mesh in place. The steel wool greatly increased the pressure and resistance of this set-up over the initial set-up.

When this configuration was tested it was found that a significant amount of the Nitrogen was still being lost. The foam that was being produced came out of the nozzle pipe at a very slow rate and was very thick, resembling shaving cream. It had an expansion ratio of about sixty which was far to low for our application.

Several different configurations were tried using the steel wool. Different thickness and densities of steel wool were tried with no success. The steel wool had too great a resistance. The Nitrogen was being forced to find channels of lower resistance through the steel wool and was bypassing the solution completely and leaving it behind.

Based on this observation we tried a configuration where a thin layer of steel wool was held in place in the middle of the pipe by a layer of mesh and after a 50 mm gap another layer of mesh was placed over the pipe opening. The thinking was that the gap would be filled up by foam created out of the steel wool and then pushed out of the mesh by the excess gas creating thoroughly mixed, higher expansion ratio foam. When this configuration was tested it worked somewhat better but the expansion ratio was still too low and a significant amount of Nitrogen was still being lost.

Our testing with the steel wool indicated that it created too much resistance for the foam solution. The solution needed to be able to travel at the velocity of the Nitrogen through the pipe. The steel wool forced the solution to slow down while the Nitrogen was still going through at the same rate.

What was needed was a configuration that enabled the Nitrogen and the solution to become well mixed without significantly impeding the movement of the Nitrogen through the nozzle pipe. It was determined that a two stage set-up utilizing layers of wire mesh screen could be used. Three layered pieces of screen were formed into a cone shape and inserted into the nozzle pipe covering the spray nozzle. The length of the cone is 75 mm. This cone is pressed against the walls of the nozzle pipe and ends with a flat spread across the nozzle pipe. There is then a 75 mm open area and then two layers of screen cover the pipe opening [see Figure 11]. The full cone solution spray nozzle is used in this configuration. The spray nozzle is able to completely coat the cone screen with solution. Unlike with the steel wool, the resistance is low enough through the wire mesh cone that the gas is not forced to create channels of lower resistance and can pick up the solution off of the screen without being significantly slowed down. Looking through the side of the plastic nozzle pipe, it can be observed in the gap between the cone screen and the second set of screens that foam with fairly large bubbles is being created out of the cone screen. This initial foam from the cone screen is able to completely coat the second set of screens covering the nozzle pipe opening and pick up any Nitrogen that was able to by-pass the cone screen and creates foam with a desired expansion ratio of 160 to 250. The two-stage, wire mesh screen set-up provides the proper amount of resistance to enable the creation of the desired foam.

The use of three layers of wire mesh for the cone screen and two layers for the pipe opening was determined through experimentation to provide the proper amount of resistance needed to produce the desired foam with an acceptably low amount of Nitrogen loss. The screen being used is an aluminum screen with 1.6 mm^2 mesh size. After it was determined that the cone configuration was to be used an aluminum lattice frame was created in the shape of the cone that the wire mesh could be fitted over. This allows easier insertion of the cone into the pipe and better reproducibility.

2.2.4 Expansion Ratio

It is desirable to be able to predict the expansion ratio of the foam based upon the system configuration. The goal is to have a configuration that can produce a range of expansion ratios of 100 to 300 by changing the settings of the system and by using spray nozzles with different spray rates.

There are two ways of changing the expansion ratio. The first is to hold the flow of Nitrogen gas constant and change the rate of output of the foam solution. The other is to hold the flow of foam solution constant and change the Nitrogen gas flow. The system is set up to hold the gas flow constant and vary the solution flow allowing for high flow momentum through the Nitrogen nozzle, which is required for good mixing. This approach is preferred to retain high momentum thus promoting mixing and high through put, which will result in fast delivery of the foam.

The expansion ratio is measured using pre-weighed buckets with volumes of 16 L. The buckets are filled with foam and re-weighed. The weight of the foam corresponds to a specific expansion ratio (see Figure 12). A pressure of 448 kPa was used for most tests since at this pressure the expected Nitrogen delivery is 230 L/min (see Figure 13). This allows for some Nitrogen bypass while still delivering at least 200 L/min.

The first nozzle that was tested (BETE WL ½) delivered 1.89 L/min at 275 kPa on the liquid flow gauge [see Table 2]. To achieve this operating pressure the flow valve needs to be set at a Cv of 0.01. With these settings an expansion ratio of 120 was obtained.

To achieve a higher expansion ratio a smaller nozzle was necessary. The second nozzle (BETE WL ¼) delivers half the flow of the first. At 275 kPa it delivers 0.95 L/min [see Table 1]. With the flow valve set at a Cv near 0.05 and the flow gauge at 275 kPa the expansion ratio is 220.

Ideally, to achieve expansion ratios higher than 220 a smaller spray nozzle would be used. However the BETE WL ¼ spray nozzle is the smallest available with the same characteristics.

The amount of Nitrogen lost was also checked at expansion ratios of 120 and 220. This was checked by timing the filling of several 16 L buckets and then computing the L/min delivered. This was then compared to the expected L/min at an operating pressure of 448 kPa (230 L/min). The experiments show a loss of 10 -15% of the Nitrogen. This is an acceptable rate of loss. The main mechanism for loss of Nitrogen is by the popping of large bubbles in the foam.

2.3 Foam Performance

NFPA 11 (Standard for Low-, Medium-, and High Expansion foam) has details on the selection of, installation and testing of foam fire protection systems. Appendix C in NFPA 11 contains information on how to test a foam product for Expansion Ratio and 25% drainage time. Since the system that is designed in this project is novel, NFPA 11 does not provide much useful information to us. The characterization tests presented in Appendix C of NFPA 11 are not used. The tests described in Sections 2.3.1 to 2.3.3 are not based upon any standardized tests that we are aware of. The tests are designed to provide some basic information about how the foam product will behave within the engine compartment of a vehicle.

2.3.1 Flow Characteristics

In the engine compartment of an automobile there is space between the engine equipment and the hood. There are also many small openings that lead to the ground underneath the automobile. The optimal foam will fill the open area above the equipment and then be pushed down into the openings. It will not readily flow out of the bottom of the engine on its own but only through pressure from above.

This behavior can be modeled using boxes with dividers. The flaps that cover the top of the boxes are extended parallel to the sides of the boxes and taped together. The dividers are than moved into this extended area leaving a fully enclosed open area above it [Figures 14 and 15]. The open area represents the space under the hood, while the channels created by the dividers represent the openings in the equipment. The foam is injected into the open area through an opening in the side of the first box and we observe how the foam fills the open space and how it flows into the channels. Multiple boxes are connected and openings are cut between them creating one long open region. The foam is injected at one end of the set-up and the test is stopped when foam starts to exit from the channels.

Three different set-ups where tested, each with different channel sizes. The first box set-up was tested using foam with expansion ratios of 120 and 220. The other two set-ups only used 220-expansion ratio foam.

TABLE 5 – Box and Channel Dimensions

Set-Up #	Head Area (cm)			Channels (cm)			
	Length	Width	Height	Length	Width	Height	Total
1 (Figure 16)	95	42	42	11	11	25	36 (4x9)
2 (Figure 17)	80	34	44	8	8	28	36 (4x9)
3 (Figure 18)	55	40	15	5	10	18	48 (4x12)

When the 120-expansion ratio foam was injected into box set-up #1 it did not readily flow through the top open area. The foam only traveled to the sixth row were it flowed down through the channels (see Figure 19). It was not pushed through by pressure from above but rather was pulled down by its own weight. When the 220-expansion ratio foam was injected into box set-up #1 it flowed through and filled the top open area and was being pushed, rather than flowing through the channels. The foam reached all the channels before foam started to exit from the bottom of the channels (see Figure 20). The foam started to move down the channels as it reached them. The foam level in the channels decreased as it moved away from the first row. Once the foam started exiting from the channels it did not simply fall to the floor like the 120-expansion ratio foam did. It hung below the box connected to the foam above it. This is the desired behavior.

Box set-up #2 has slightly smaller width channels than box set-up #1. This creates more resistance for the foam. When foam is injected into box set-up #2 the foam completely filled the top open area and is starting to move down all channels before it starts to exit from the channels. Again the foam is being pushed through the channels by pressure from above, not flowing, and would hang below the bottom of the box. As in box set-up #1, the foam starts to move down the channels as it reaches them.

Box set-up #3 has much smaller channels than the other two set-ups resulting in much higher resistance. When foam is injected into box set-up #3 the top open area was completely filled before the foam starts to move into the channels. The foam then moved down the channels evenly across all channels (see Figure 21).

This behavior is consistent with the typical manifold/channel flow distribution. As the flow resistance in the channels increases the flow uniformly spreads throughout the manifold. In this case as we progress to smaller channel dimensions we observe an increased uniformity in the channel flow distribution.

2.3.2 Foam Adhesion/Cohesion

Two different tests were done to test the adhesion / cohesion properties of the foam, the hang test and the wall test. The hang test evaluates the ability of a column of foam to hang freely after exiting from a vertical pipe (cohesion). The wall test evaluates the ability of the foam to pile up in layers against a wall without collapsing or flowing down (adhesion).

For the hang test an aluminum pipe, 0.3 m long with a diameter of 0.1 m, was attached to the bottom of a box. The box has an opening on one vertical face to feed in the foam. On the opposite face a flap is cut into the side. The flap can be opened and closed in order to control the flow of foam into the pipe. When the flap is open the foam will freely flow out of the opening and little foam will be pushed through the pipe. During the test the flap will be closed until a maximum amount of foam is hanging from the pipe and then opened so that the foam stops flowing and hangs from the pipe exit. The hanging foam is then photographed and measured.

When tested, it is found that 220-expansion ratio foam would hang 12 inches below the pipe outlet without falling off (see two different tests in Figures 22 and 23). This should provide a suitable level of cohesion considering the height of the engine compartment and its ground clearance.

For the wall test foam is sprayed up against a brick wall in a single layer piled upon itself. The foam is piled up until it collapsed or flows down from beneath the pile. The piles were approximately two feet wide. The foam was applied in a zigzag pattern up the wall.

For an expansion ratio of 120 the foam did not adhere to the brick wall very well. The foam started to flow down from of the pile and away from the wall at a height of about 0.15 m.

At an expansion ratio of 220 the foam behaved differently. The foam was able to adhere to the brick wall easily and did not flow down from the pile. The foam was piled to a height of 90 cm and then the entire pile collapsed at once.

The foam with an expansion ratio of 220 adheres to the brick wall well enough that a block of foam 0.24 m square will hang freely in the middle of the wall with no support for approximately thirty seconds (see Figure 24).

2.3.3 Foam Hot Plate Tests

Many of the components that are present in an automobiles engine compartment operate at elevated temperatures during normal use. The foam must be able to adhere reasonably well to these hot surfaces and not break down too quickly. The hot plate test is used to observe how the foam reacts to exposure to elevated temperatures. A variable temperature hot plate was covered with a flat aluminum pan and placed so that the pan was at a 45-degree angle (see Figure 25). The plate was heated to a temperature of 110 C (230 F). Foam was then applied to the surface of the heated pan and observed (see Figure 26).

The surface of the pan is initially at a temperature of 110 °C. When the foam is applied to the hot surface it begins to slide down and off the pan. Only the top of the pan is heated and when the leading edge of the foam starts to move across the cooler sides of the pan it stops and the rest of the foam piles up on top of it. Once stopped, a gap is formed between the foam and the hot pan. The gap is about 30 mm and is maintained for 1 or 2 minutes (see Figures 27 and 28). This indicates that the convective and radiative heat transfer is sufficiently reduced to affect marginally the foam across the gap. As the foam degrades, it collapses against the hot plate and is completely vaporized.

This test, in conjunction with the cohesion/adhesion tests, indicates that the foam may survive in the engine compartment in regions adjacent to hot surfaces.

The foam will also be able to absorb heat from the hot surfaces providing cooling. The water within the foam is capable of absorbing about 2400 kJ/kg of water. The foam will be vaporized near sources of heat such as hot engine components or a fire source so the total heat removal capabilities of the foam will most likely not be fully utilized. Therefore, estimating that 0.1 L of solution vaporizes in one minute, it follows that the foam will be capable of removing about 4 kW of energy from the compartment.

3 – SCENARIOS AND TEST MATRIX

Two general scenarios are considered: a) normal and b) rollover. The normal scenario is the major focus of this thesis. Rollover and partial rollover scenarios will require some initial discussion and evaluation of the various possibilities identifying the details of the various possible ignition sources and fuel distribution as the automobile configuration changes. In this thesis we will focus on the normal scenario where the car is in its original upright position and we will examine one possible rollover scenario.

3.1 Scenarios

3.1.1 Normal Scenario

The car remains in its upright position and the foam is deployed along with the airbag(s). The fire may initiate immediately after the crash within the engine compartment. In this case, we postulate an electrical ignition source near the battery and a gasoline leak at the same location. The NIST report suggests a fuel leak of the order of 200 mL/min. The paper by Mangs & Keski-Rahkonen suggests that the tenability of the passenger cabin is compromised within 5 minutes from ignition. Therefore, it is reasonable to ignite an adequate volume of gasoline at the initial time to represent the worst possible condition in terms of fire growth.

The testing site at MFRI has strict no-spill policies. Therefore, we will simulate the required fire load with pool fires rather than with fuel leaks. Babrauskas (2002) provides the following correlation for radiative pool fires:

$$HRR = H\ m\left(1-e^{-kD}\right)\frac{D^2}{4}$$

Where HRR is the heat release rate in kW,

H is the effective heat of combustion in kJ/kg

and = 43,700 for gasoline

m is an empirical constant in kg/m^2s

and = 0.055 for gasoline

k is an empirical constant in m^{-1}

and = 2.1 for gasoline

D is the pool diameter in meters

The prescribed heat release rate form the NIST report is achieved with a pool of fuel of 0.3 m in diameter (80 kW) and an initial fuel volume of 1 L. The pool fire duration is of 5 minutes and should suffice to challenge the suppression capability of the foam product. The foam is initially deployed at a rate of 4 L/s. We will experiment with this nominal test first and make any changes to the flow rate or expansion ratios that are necessary.

Within the normal scenario we will also explore a second possibility. Here the foam is successfully deployed and initial fires in the engine compartment are suppressed. The foam now degrades under the effect of temperature and time. A pool fire is initiated under the engine compartment sometime after the crash. We will investigate the performance of the foam in eliminating or curtailing re-ignition. Two effects will be investigated: the effect of fire load and the effect time. We will consider an ignition time for the pool fire of 5 minutes after the foam deployment. The pool fire will be of about 0.3 m in diameter (80 kW).

For all the experiments the depth of the pool is estimated at about 14 mm. Therefore, we will use shallow rectangular or round trays with the rectangular trays having reasonable aspect ratios in their horizontal dimensions with total surface area equivalent to the 0.3 m diameter pool. As an example, this objective could be achieved with rectangular trays 0.3 m by 0.23 m.

The paper by Jensen and Santrock mentions that during their testing the vehicles were kept at ambient temperature initially. A suitable means for heating the engine compartment of our test automobiles is not available. During testing the engine compartments of the vehicles are not artificially heated, they are kept at the ambient temperature initially.

3.1.2 Rollover Scenario

We have discussed the possibility of collecting data for the rollover scenario. In searching the literature for some standard conditions on which to base our testing, we could not define a finite number of scenarios to consider. One key element is the fuel distribution in rollover conditions:

- Where the fire is most likely originated?
- What fuel leak or fuel volume should be used?
- What is the relationship of the fire with the passenger cabin?

This last question appears to be significant because of the likely breach of the passenger cabin due to the most likely breakage of windshield and windows.

One possible scenario would be that an automobile has rolled over onto its top, fuels from the engine have leaked down onto the inside of the hood and an ignition occurs directly below the engine in this pool of fuel. When the foam is deployed it should fill the area between the engine and the hood and be able to smother the pool fire. This scenario will be tested so that some data is gathered for how our suppression system responds in a rollover situation.

We recommend conducting a more thorough investigation of the possible configuration of the rollover scenario based on the three questions raised above. Upon formulating a finite set of test conditions, we could prioritize them and conduct a more meaningful investigation that could lead to the evaluation of the proposed fire protection system in the rollover scenario.

3.2 Testing Procedures and Instrumentation

An appropriate number of initial tests are performed to try and contain or extinguish pool fires at the battery location. These initial tests are used to determine whether or not the foam flow rate and expansion ratio is correct before moving on to the official tests.

For the first test, at the initial time a pool fire at the battery position in the engine compartment will be ignited, the hood will be closed and the car will be allowed to burn uninhibited. This test will provide baseline data to compare to the suppression tests. For the second and third test, at the initial time a pool fire at the battery position in the engine compartment will be ignited, the hood is closed and the foam is deployed in rapid sequence. For the fourth test, the foam is deployed and a pool fire located on the ground under the engine is ignited 5 minutes after the foam deployment. For the fifth test, the automobile is rolled over onto its top, at the initial time a pool fire located inside the hood and directly underneath the engine is ignited and the foam is deployed in rapid sequence.

The cars are instrumented with several type K thermocouples (TC's). These thermocouples are positioned at different positions and elevations within the engine compartment to monitor the spread and extinguishment of the fire.

A camcorder is available to record the temporal evolution of the test. The camcorder and the TC's are synchronized with the initial ignition time by monitoring the temperature near the fuel pool and the image of the fire ignition. The hood is in a closed position with an appropriate deformation associated with a moderate frontal impact. For guidance we tried to duplicate the geometry of the previous experiments as documented in the NIST report.

3.3 Test Matrix

The following test matrix is proposed:

TABLE 6 – Test Matrix

Test Identifier	Fire Location	Timing of Foam Deployment
Initial Tests – Ford LTD: Burn #1	Near the Battery	Concurrent with Ignition of Fuel
Initial Tests – Ford LTD: Burn #2	Near the Battery	Concurrent with Ignition of Fuel
Test #1 – Un-Suppressed Burn of Saturn Compact Sedan	Near the battery	No Foam. Fire Burns Uninhibited.
Test #2 – Suppression – Nominal – Chrysler Mid-Size Sedan: Burn #1	Near the battery	Concurrent with Ignition of Fuel

Test #3 – Suppression – Nominal – Chrysler Mid-Size Sedan: Burn #2	Near the battery	Concurrent with Ignition of Fuel
Test #4 – Re-Ignition – Nominal – Chevy Cavalier Sedan	On the ground below the engine compartment	Foam deployment starts five minutes before fire is ignited
Test #5 – Rollover – Mercedes Benz	On the hood directly below engine	Concurrent with Ignition of Fuel

4 – FULL SCALE AUTOMOBILE BURN TESTS

4.1 Initial Tests – Ford LTD: Burn #1

4.1.1 Test Set-Up

The first automobile used to test the foam generator is a 1980 Ford LTD Crown Victoria [Figure 30]. The front end of the Ford is intact, not crumpled. The contents of the engine compartment are intact except for the battery, which had been removed from its position in the front, left of the compartment. The foam generator is positioned within the engine compartment in the back, right behind the air filter box. The stainless Nitrogen gas and solution tubes are inserted through a hole that was punched in the grill. The nozzle pipe is positioned facing upward. For this and future tests the plastic nozzle pipe that had been used throughout the characterization testing was replaced by an equivalently sized piece of steel pipe.

In actual use the foam generator should be located near the firewall, with the nozzle pipe injecting foam near the back of the engine compartment. The rigid nature of the stainless steel piping limited our ability to position the foam generator. In order to get the foam injected at the desired site within the engine compartment 8-inch diameter, flexible, aluminum HVAC duct pipe was attached to the nozzle [Figure 30 and 31]. The flexible duct pipe was attached to the nozzle pipe using duct tape. The flexible duct pipe is positioned so that the foam is injected into the engine compartment at the desired position. Since the diameter of the flexible duct pipe is larger than the diameter of the nozzle it is assumed that it will have a minimum affect on the physical structure of the foam. In actual use the flexible duct pipe would not be necessary and the foam would be injected directly into the engine trough the nozzle pipe.

As discussed in Section 3.1.1, a fire size of 80 kW is desired. In order to achieve this fire size a circular pan with diameter = 0.3 m is needed. It was decided that a rectangular pan with an equivalent surface area would fit into the opening left by the battery better than a circular pan. A 9 x 14 inch aluminum-baking sheet is used. The pan is placed into the opening left by the battery and leveled. The pan is filled with gasoline to a depth of about 14 mm [Figure 32]. Once lit, this set-up should produce an 80 kW fire for a duration of about 5 minutes.

A section of wood from a 2 x 4 was used to bend the hood. Placing the piece of wood across the middle of the engine compartment, parallel to the front of the car, and closing the hood on it bent the hood. This creates gaps on either side of the hood with a peak of about 4 inches at the center. This simulates a post-collision scenario were gaps have been created around the edges of the hood by crumpling.

The foam generator was set to operate at 448 kPa (65 psi). At this pressure approximately 200 L/min of foam with an expansion ratio of about 220 is produced. Before starting the test the system was primed. This consisted of opening the fluid line so that the solution tubing could fill with foam solution and be emptied of air. Once primed the system produces foam as soon as both the solution and gas lines are opened.

Once everything was set up the test was started. The hood of the car was open initially so that the gasoline could be lit easily. The gasoline was lit using a flare. As soon as the gasoline was lit the hood was closed and the foam generator was turned on.

4.1.2 Test Observations

It is immediately obvious that the foam being produced did not have the desired characteristics. The foam is being emitted much slower than expected and was very thick (its expansion ration was too low). It is obvious that the foam had no chance of containing the fire and the test was stopped.

The main problem with the test and the cause of the low expansion ratio was Nitrogen gas leaking from around the base of the new metal nozzle pipe. The new metal nozzle pipe did not fit as snuggly as the plastic nozzle pipe had and did not form a seal when inserted into the generator block. This allowed the Nitrogen gas to easily leak out instead of becoming part of the foam.

A secondary problem with the test was the observation that based on fire size, spread rate and engine compartment volume a flow rate of 200 L/min of foam would not have been sufficient to extinguish the fire within a reasonable amount of time, if at all.

4.1.3 Test Results

As a result of the initial test, it was decided that two changes needed to be made to the foam generator. First, a system for creating a seal between the nozzle pipe and the block would be introduced. Second, the flow (L/min) of foam from the device would be increased by increasing the flow of Nitrogen to the device.

4.1.4 Changes to the Device as a Result of Initial Test #1

A better seal between the nozzle pipe and the block was created by using a thick rubber O-ring. The O-ring has the same diameter and thickness as the nozzle pipe. In order to maintain the seal the nozzle pipe needs to be held down with constant pressure onto the O-ring. This is done using a screw on clamp. Four threaded holes are drilled into the corners of the block around the opening for the pipe. The outside of the nozzle pipe is trimmed (decreasing the outer diameter) from the top of the nozzle pipe down to about an inch above were the nozzle pipe sits in the block. This creates a small ledge in the nozzle pipe. A rectangular aluminum metal plate with the same length and width of the block is fashioned. The plate has holes drilled into it that correspond to the holes in the block. A hole is hollowed out of the plate that is the same size as the decreased outer diameter of the nozzle pipe. The plate fits over the nozzle pipe and sits on the ledge. Four screws are used to clamp the plate to the block and create constant downward pressure onto the O-ring, thus creating a good seal [Figure 33].

There are two options available to increase the flow of Nitrogen to the foam generator. The first is to increase the overall Nitrogen pressure within the system. The second is to increase the size of the hole in the generator block that the Nitrogen is flowing through. The second option is more desirable because it allows us to keep the operating pressure for the system the same while still increasing the Nitrogen flow.

The original Nitrogen inlet was creating using a 3/32-inch drill bit and delivers about 230 L/min of Nitrogen at an operating pressure of 448 kPa (65 psi). The inlet was re-drilled using a 7/64-inch drill bit. The new area of the Nitrogen inlet is 6.07 mm^2. Using the calculation method shown in Section 2.2.1 the new mass flow rate is given by:

$$\dot{m} = P_{0,kPa} * (1.41 x 10^{-5}) \text{ ; (kg/s)}$$

Using this new flow data a new Nitrogen flow chart is created [Figure 34]. The Nitrogen flow at the desired operating pressure of 448 kPa (65 psi) is about 315 L/min. Allowing for leakage, this should provide a flow of foam of about 300 L/min.

In order to create foam with an expansion ratio of 220 with the increased Nitrogen flow the flow of the foam solution to the spray nozzle must also be increased. The L/min of solution needed is calculated by dividing the L/min of Nitrogen available by the expansion ratio. For a Nitrogen flow of 300 L/min, 1.4 L/min of solution is needed. The characteristics of the BETE WL ¼ nozzle that was used for the first test are shown in Table 1 of Section 2.1.4. The liters of liquid delivered versus pressure for this nozzle is also plotted in Figure 35. Figure 35 shows that this nozzle will not be capable of producing 1.4 L/min of solution since the maximum solution pressure on the spray nozzle will be about 448 kPa (65 psi). A larger spray nozzle is necessary, so the BETE WL ½ [see TABLE 2] is considered. The liters of liquid delivered versus pressure for this spray nozzle is plotted in Figure 36. It can be seen from Figure 36 that this larger nozzle can deliver 1.4 L/min of solution when the solution pressure on the nozzle is 22 psi (152 kPa). BETE WL ½ nozzle was installed on the generator block and the solution flow valve was calibrated to produce a pressure of 22 psi in the solution line.

4.2 Initial Tests – Ford LTD: Burn #2

4.2.1 Test Set-Up

The set-up for the 2nd burn of the Ford LTD is basically the same as the first burn described in Section 4.1.1. The only differences between the first burn and the second burn are the changes that were made to the foam generator to increase the flow rate and the addition of some plastic pieces around the previous burn area to replace the small amount of plastic and rubber tubing that was burned during the first test before the fire was extinguished.

The second test is initiated in the same manner as the first test. The pan is placed into the opening left by the battery and filled with gasoline. The solution line is primed. The fire is started with the hood up and then immediately closed. The foam generator is turned on at the same time as the fire was started.

4.2.2 Test Observations

Unlike the first test the foam that is being generated appears to have the correct characteristics. It can be seen through the openings at the sides of the hood that the foam flows out from the flexible duct pipe across the top of the engine and fills the open area between the engine and the hood first. Once the open area has been filled the foam starts to fill downward into the spaces around the engine. Due to the large size of the engine compartment and it's relatively open configuration it takes approximately 3 minutes to completely fill the engine compartment and have foam start to be pushed out of the compartment by pressure from above. This indicates a total open area of [800 to 900 L] in the compartment. The foam does not move very quickly across the engine compartment and takes some time to approach the fire.

As the foam moves across the top of the engine it forms a semi-circle around the pan containing the gasoline fire. It takes about 1 minute for the foam to surround the fire. The foam contains the fire to the front left corner of the engine compartment, but it is unable to impinge upon it directly. Once the foam has encircled the fire the flames are seen to be angling away from the foam, out of the car, through the openings around the hood. Once the foam is in place the fire is unable to spread at all through the engine compartment. The fire is able to consume some of the paint on the outside of the hood and car side panel, but there is no actual fire spread outside of the compartment. Figures 37 through 40 show pictures of the car during the fire and pictures of the foam filled engine compartment after the fire was extinguished.

4.2.3 Test Results

The ability of the foam to contain the fire and prevent it from spreading is a positive result. However, it would be desirable for the foam to be able to impinge upon and extinguish the flame. Observations showed that the foam was not moving very quickly across the engine. The position of the fire pan in the corner of the engine compartment made it impossible for the foam to surround the pan and cut off its paths to fresh air. In order for the foam to be able to extinguish a fire in this situation it must have a high enough fill rate to be able to overcome the evaporation rate of the foam that is occurring close to the fire. Once the filling rate is great enough the foam will be able to roll over the top of the fire and snuff it out. In order to increase the fill rate of the foam it was decided that the Nitrogen flow needed to be increased again.

4.2.4 Changes to the Device as a Result of Initial Test #2

For the previous test the Nitrogen inlet was increased from a diameter of 3/32-inch to 7/64-inch. The inlet was re-drilled again using a 1/8-inch drill bit. The new area of the Nitrogen inlet is 7.92 mm^2. Using the calculation method shown in Section 2.2.1 the new mass flow rate is given by:

$$\dot{m} = P_{0,kPa} * (1.83 \, x \, 10^{-5}) \text{ ; (kg/s)}$$

Using this new flow data a new Nitrogen flow chart is created [Figure 41]. The Nitrogen flow at the desired operating pressure of 448 kPa (65 psi) is about 415 L/min. Allowing for leakage, this should provide a flow of foam of about 400 L/min.

In order to create foam with an expansion ratio of 220 with the increased Nitrogen flow the flow of the foam solution to the spray nozzle must also be increased. The L/min of solution needed is calculated by dividing the L/min of Nitrogen available by the expansion ratio. For a Nitrogen flow of 400 L/min, 1.82 L/min of solution is needed. Referring to Figure 36, it can be seen that a solution pressure of 37 psi (255 kPa) is needed at the spray nozzle to deliver this flow. This means that the same spray nozzle, BETE WL ½, can be used to deliver the new flow.

4.3 Test #1 – Un-Suppressed Burn of Saturn Compact Sedan

4.3.1 Test Set-Up

The purpose of this test is to gather basic information about how a fire that starts within the engine compartment of a car, near the battery, spreads. A Saturn Compact 4 door sedan is used for the test. The car had been in a front-end collision and had some minor damage to the front of the car. The engine compartment was mostly intact, with little deformation [Figure 42]. The hood was bent in the same manner as the Ford LTD providing gaps along the edges between the hood and the car. A 0.3 m diameter, circular pan is used to hold the gasoline for this test [Figure 43]. The pan has a similar area to the rectangular pan used in the Ford LTD tests. The pan is placed in the front right of the engine compartment in the space left by the battery. The pan is filled with enough gasoline to burn for 5 minutes. The foam suppression system was not used for this test. Once the fire is started, it is allowed to burn uninhibited. In order to measure the spread of heat and fire within the engine compartment seven Type K thermocouples (TC's) are placed within the engine compartment. Three of the TC's are placed on the top of the engine at the corners; not including the corner the pan is in. The other four TC's are placed around the bottom of the engine at the four corners. The two lower, front TC's are placed in the wheel wells, between the tires and the engine [Figure 44].

The fire is started with the hood open. The hood is closed immediately and the fire is allowed to burn uninhibited.

4.3.2 Test Observations

Initially the fire seems to be burning on the gasoline only. Flames are seen emitting from gaps between the hood and the body of the car [Figure 45]. The flames fluctuate between the gap on the right side of the car and the gap above the front right of the car. The fluctuation between positions seems to be controlled by the wind. At about 50 seconds the flames start to emit from the right side gap and the front right gap simultaneously and are sustained for the remainder of the burn. This indicates that the fire has moved from the pan and is increasing in size.

At about 75 seconds flames start to emit from the gap between the hood and the body of the car on the left side. This indicates that the fire has spread across the engine compartment.

At about 100 seconds the fire visible outside of the car approximately doubles in size. The right front of the car is totally engulfed in fire and the top of the hood starts to burn.

The fire is allowed to burn for 180 seconds and is then extinguished with water.

4.3.3 Analysis of Thermocouple Data

The temperature data collected during the test is shown in Figure 46. It can be seen from the data that the fire and heat stayed above the engine and did not reach the lower TC's during the duration of the test. The three TC's located on top of the engine all show significant exposure to heat and fire. Concurrent with the start of the fire, TC 9 experiences the largest initial temperature jump. This makes sense since it is the TC closest to the pan and it is also located by the right side gap between the hood and body of the car. Observations show that TC 9 was continuously being directly exposed to flames during the burn. TC's 3 and 10 experience smaller initial temperature jumps because they are initially only being exposed to hot smoke. TC 3 initially has a lower temperature than TC 10 because, based on position, it has better access to fresh air to help cool it. TC 3 experiences a significant raise in temperature after 80 seconds. This is caused by the fire having spread across the engine to the left side of the car to impinge directly upon the TC. TC 10 stays fairly steady throughout the test. This indicates that flames did not reach the left, back corner of the engine compartment before the fire was extinguished.

4.4 Test #2 – Suppression – Nominal – Chrysler Mid-Size Sedan: Burn #1

4.4.1 Test Set-Up

This test sees whether the foam generator, with the changes made after Initial Test #2, is able to extinguish a pan fire located in the battery position of an engine compartment. The automobile used for this test is a Chrysler mid-size sedan. The automobile was initially intact. The sides of the hood are bent as described previously [Figure 47]. The pan for this fire is located in the front right of the car in the opening left by the battery. The rectangular pan is used for this burn [Figure 48]. The foam generator is located below the engine. A length of the flexible, 8-inch diameter, HVAC duct pipe that was used for the Ford LTD tests runs up through an opening in the engine compartment to the top of the engine. The flexible duct pipe is positioned pointing towards the rear of the car, with the opening pointing at a flat angled surface on the engine block [Figure 49 and 50]. This should create an even distribution of foam throughout the engine compartment. The foam generator is set to operate at 448 kPa (65 psi). This will generate approximately 400 L/min of 220-expansion ratio foam.

4.4.2 Test Observations

The fire is started with the hood open. Once the fire is started the hood is closed immediately and the foam generator, which had been primed before the test began, is started. As in the previous tests most of the flames were coming out of the gap between the hood and the body of the car near the fuel pan [Figure 51]. It takes the foam about 30 seconds to approach the fuel pan. At first, the foam forms a semi-circle around the pan, but cannot encroach upon it. After about 10 seconds the foam is able to rollover the top of the fire and extinguishes it. The fire is completely extinguished within 40 to 45 seconds of ignition. The foam generator is allowed to operate for 70 seconds total. The engine compartment is completely filled and foam is starting to protrude from the openings around the hood at about 60 seconds. A small amount of foam is pushed down and out of the bottom of the engine compartment onto the ground. This did not occur until the last few seconds of the test.

After the test is complete the hood is opened so that the engine compartment can be examined. There is still gasoline in the pan with foam lying on top of it, so the fire was definitely extinguished by the foam. The top of the engine is completely covered with foam [Figure 52]. Looking from underneath the car it could be seen that the spaces within the engine have also been completely filled with foam. There are no obvious hot spots in the compartment and no smoke is being emitted. The hood is re-closed and the foam is allowed to sit undisturbed. After 10 minutes the hood is re-opened. Although there had been some breakdown of the foam (approximately 20 to 30%), the engine is still completely encapsulated in foam and liquid is not visibly leaking down onto the ground.

4.5 Test #3 – Suppression – Nominal – Chrysler Mid-Size Sedan: Burn #2

4.5.1 Test Set-Up

This test uses the same set-up as the Test #2. There are two differences between this test and Test #2. First, the engine compartment is equipped with TC's in order to measure the movement of heat within the engine compartment. The TC's are arranged on top of the engine in the pattern shown in Figure 53. TC 10 is outside of the engine compartment near the gap between the hood and the body and is intended to measure the spread of flames outside of the engine compartment and toward the cabin of the car. Second, a different type of foam concentrate is used. The foam used for this test and tests 4 and 5 is 'Chemguard ECOGUARD 3% F3 Synthetic, Fluorine Free Foam'. The foam contains no glycol ether, alkyl phenol ethoxylates or fluorine. As a result, it is 100% biodegradable and presents a low environmental impact. The foam should provide the same level of performance as the Ansulite 3x3 foam used for all previous work. The manufacturer recommends that for hydrocarbon fires the foam will be most effective if used in a concentration of 7 to 9%. For this test and tests 4 and 5 the foam concentration will be 8%. No other changes are made to the foam generator. The generator will still operate at 65 psi and will produce foam with an expansion ratio of about 220.

4.5.2 Test Observations

The fire is started with the hood open. Once the fire is started the hood is closed immediately and the foam generator, which had been primed before the test began, is started. As in the previous tests most of the flames are coming out of the gap between the hood and the body of the car near the fuel pan. It takes the foam about 25 seconds to approach the fuel pan. At first, the foam forms a semi-circle around the pan, but cannot encroach upon it. After about 5 seconds the foam is able to rollover the top of the fire and extinguishes about 90% of the fire. A small amount of fire remains near the grill of the car and is extinguished within 20 seconds. The fire is completely extinguished within

50 seconds of ignition. The foam generator is allowed to operate for 70 seconds total. The engine compartment is completely filled and foam is starting to protrude from the openings around the hood at about 60 seconds [Figure 54]. A small amount of foam (about 2 liters) is pushed down and out of the bottom of the engine compartment onto the ground. This did not occur until the last few seconds of the test.

After the test was complete the hood is opened so that the engine compartment can be examined. There is still gasoline in the pan with foam lying on top of it, so the fire was definitely extinguished by the foam. The top of the engine is completely covered with foam [Figure 55]. Looking from underneath the car it could be seen that the spaces within the engine had also been completely filled with foam. There are no obvious hot spots in the compartment and no smoke is being emitted. The hood is re-closed and the foam is allowed to sit undisturbed. After 10 minutes the hood is re-opened. Although there had been some breakdown of the foam (approximately 20 to 30%), the engine is still completely encapsulated in foam and liquid is not visibly leaking down onto the ground [Figure 56].

4.5.3 Analysis of Thermocouple Data

Figure 57 shows the temperature information collected by the TC's during the burn. The TC data backs up the observed time for the extinction of the fire. The data also indicates the manner in which the foam encroached upon the fire. The point on a TC curve were the temperature starts to decline corresponds to when the foam reached that TC. It appears that the foam did not encroach on a direct line from the foam generator, but by circling around the generator and approaching from the left side of the pan. It appears that the foam reached TC-9 first. Because of the intensity of the fire the foam could not impinge directly upon the fire from that direction and stopped. As the foam fills the compartment it totally encircles the fire pan. As the foam approaches from the left TC-4 is covered and the foam starts to move over the pan. The foam moves across the front of the pan, cutting it off (on one side) from outside air and covers TC-2. Once the pan is isolated from its main source of air the fire intensity is diminished and the foam is able to move onto the pan from all sides. TC-3 is reached and the fire is completely extinguished. TC-10 (which was outside of the engine compartment) starts to decline since there are no more hot gases being produced to impinge upon it. TC-10 shows the most gradual fall off in temperature since it is never actually covered with foam.

4.5.4 Results from Tests #2 and 3

During these tests an 80 kW fire, at the battery position, was successfully extinguished by the Nitrogen foam fire protection system. The changes made after the two Ford LTD tests enabled the system to be able to reach and overwhelm the fire in a short period of time before the fire could spread with any significance throughout the engine compartment. The switch from Ansulite 3x3 foam solution to ChemGuard Ecoguard 3% F3 foam solution did not negatively affect the ability of the foam generator to extinguish the fire in Test #3.

4.6 Test #4 – Re-Ignition – Nominal – Chevy Cavalier Sedan

4.6.1 Test Set-Up

This test is designed to test the durability of the foam in a common post-collision fire scenario. The fire will originate in a pan of gasoline that is placed on the ground, underneath the engine compartment. The pan will contain enough gasoline to sustain an 80 kW fire for 5 minutes. The engine compartment of the car will be filled with foam as in Tests #1 and 2. The foam will be allowed to sit for 5 minutes before the fuel is ignited.

This models a situation were there has been a fuel leak onto the ground, which is ignited sometime after the collision. The goal of the test is not to see whether or not the fire can be extinguished, but whether the foam can protect the engine compartment from ignition during the 5-minute duration of the fire.

The automobile used for this test is a Chevy Cavalier RS sedan. The automobile had been in a front-end collision and there is extensive damage to the grill area of the car. The front end of the automobile is pushed back into the engine slightly. The engine itself and everything behind it is intact. The sides of the hood are manually bent in the same manner as the previous tests.

The foam generator is placed outside of the engine compartment. A length of flexible, 8-inch diameter, HVAC duct pipe is run through the gap between the hood and body of the car to get the foam inside the engine compartment.

The pan used for this test is the 0.3 m diameter circular pan. The pan is placed directly underneath the engine block. Enough gasoline is placed into the pan to sustain the 80 kW pool fire for 5 minutes. Pieces of drywall are placed around the perimeter of the automobile to try and prevent the wind from affecting the fire. TC's are placed throughout the engine compartment as shown in Figure 58.

4.6.2 Test Observations

The foam generator is run for 70 seconds. This produces about 460 L of foam. The areas above and around the engine are completely filled with foam. A small amount of foam is pushed out of the front of the hood above the grill. No foam fell from the bottom of the engine compartment initially. After foaming is complete the flexible duct pipe is removed from the engine compartment. The gasoline is then placed into the pan. The fire was lit 340 seconds after the foam generator had been started.

After a few seconds the flames from the fire could be seen fully penetrating the engine compartment and entering the headspace between the engine and the hood. The flames from the pan are concentrated on the left side of the engine compartment throughout the test. Occasionally flames would come out from the front of the car across the grill. After approximately 120 seconds portions of the front left of the engine are sustaining flames independently of the pool fire. After this the fire continued to gain in intensity and in smoke production. After 250 seconds water is applied to extinguish the fire. A post fire examination showed that there is no foam left in the engine compartment

4.6.3 Analysis of Thermocouple Data

Figure 59 shows the temperature information collected by the TC's during the burn. The data collected shows that the flames were indeed concentrated on the left side of the car. TC's 4, 5, 6 and 8, which were on the right side of the car, show little activity throughout the test even though it is known that at some point all of the foam had broken down within the engine compartment.

The TC's on the left side of the car give an indication of how long the foam took to break down. Initially the greatest temperature response is seen in TC's 2 and 3. They were located toward the front left of the engine compartment, on top of and in the middle of the engine. These TC's were exposed to the flames that were penetrating the engine early in the test. Initially TC's 7 and 10 did not show much response since the fire was not directly impinging on them. However, at about 120 seconds, when the engine was observed to be sustaining flames on its own there is a change in the temperature trends for all of the TC's. TC's 7 and 10 show a quick and significant increase in temperature at this point. TC 7 went from under 50 ^{0}C to over 500 ^{0}C in approximately 20 seconds. TC 10 went from under 100 ^{0}C to over 600 ^{0}C in approximately 20 seconds. TC's 2 and 3 also showed a sharper increase during this time. It can be surmised that at about 120 seconds the foam has broken down significantly throughout the engine compartment. The engine can now support flames independent of the pool fire and starts to burn. This increases the breakdown rate of the foam and the flames spread throughout the left side of the engine compartment. All of the TC's on the left side of the car are now being exposed directly to flames and a dramatic increase in temperature readings is seen.

4.6.4 Results

The foam is unable to protect the engine from ignition for a period of time greater than about 120 seconds. The goal is to provide protection against an 80 kW fire with a duration of 300 seconds. It can be surmised that at some smaller fire size the foam should be able to provide 300 seconds of protection. A goal of future work could be to determine this critical fire size. However, it appears that for 80 kW or larger fires this system configuration is not capable of providing more than 120 seconds of protection for the engine compartment.

The inability of the system to provide significant protection from pool fires underneath the engine compartment does not detract from the viability of the system since the main goal of the system is to provide protection from fires that originate within the engine compartment itself. It was decided after this test that it would not be beneficial to this project to further investigate the under-automobile pool fire scenario.

4.7 Test #5 – Rollover – Mercedes Benz

4.7.1 Test Set-Up

This test is designed to test the ability of the foam generator to extinguish a fire in a post-rollover situation. The foam generator is positioned in its expected normal position near the firewall and the top of the engine. For this test the flexible duct pipe is not needed. The car is rolled over onto its top with the hood closed, but crumpled at the sides as in the previous tests [Figure 60 and 61]. The pan of gasoline is placed on top of the inside of the hood, directly underneath the engine [Figure 62]. The pan used is the 0.3 m diameter circular pan and is filled with enough gasoline to provide an 80 kW fire for 5 minutes. TC's are placed around the top and bottom of the engine compartment [Figure 63]. The fire is lit and the foam generator, which had been primed before the test began, is turned on at the same time.

4.7.2 Test Observations

The flames from the fire impinged directly upon the engine above. The foam drops directly down onto the hood below the generator and does not fill the spaces around the engine at all. The foam spreads out from directly under the generator in all directions. The foam starts to approach the pan almost immediately. The foam encircles the pan at first and then starts to rollover the fire after about 40 seconds. The main fire is extinguished after about 55 seconds [Figure 64]. A small amount of gasoline had spilled out of the pan onto the insulation that lined the hood of the car during the filling of the pan. This spill is between the pan and the grill at the front of the car. The foam extinguishes this secondary fire after 205 seconds. This lengthy time was due to the way that the foam is moving across the inside of the hood. After the foam rolled over the pan most of the movement of the foam was to the sides, towards the gaps between the hood and the body of the car [Figure 65]. Since there wasn't much foam fill momentum left toward the front of the car the fire could not be extinguished quickly. However, there was no fire spread and the fire was eventually extinguished.

4.7.3 Analysis of Thermocouple Data

Figure 66 shows the temperature information collected by the TC's during the burn. The main TC's that show response to the fire are TC 9 and 7. These TC's are located on the left side of the engine compartment at the top and bottom of the engine. The data collected by these TC's shows that temperature starts to decrease at about 35 seconds. This backs up the observed time when foam starts to roll over the top of the fire.

4.7.4 Results

The foam was able to extinguish the pool fire for this one particular rollover fire scenario. However, not much can be said about how the system would fair in other rollover fire scenarios.

5 – SUMMARY AND CONCLUSIONS

5.1 Summary and Discussion of the Full Scale Automobile Burn Tests

The two initial tests performed with the Ford LTD demonstrated that the Nitrogen foam fire protection apparatus could be effective in containing fires that start at the battery position. The initial foam flow rate of 200 L/min was discovered to be too slow and was increased to 400 L/min. Foam with an expansion ratio of 220 was found to be able to fill the engine compartment without freely flowing down and out of the engine compartment as predicted during the initial system testing. Initial Test #2 showed that if the foam was moving slowly toward a fire it was not durable enough to overcome the heat and move over the flame. Instead foam encircled the fire and an equilibrium was established. Based upon these results further suppression testing for a fire at the battery position was carried out.

Test #1 was carried out to gather baseline data about the un-suppressed spread of a fire that starts within the engine compartment at the battery position. Observations from this test and from Initial Test #1 show that these fires spread and grow quickly and cross over into a flashover type situation were all the oxygen available within the engine compartment is being consumed within a few minutes of ignition. Based on this, it can be stated that our system must be able to fill the engine compartment with foam within the first sixty seconds after activation to be successful. If the foam is not deployed within this time a fire large enough to overcome the foam completely could develop.

Tests #2 and 3 test the ability of the Nitrogen foam fire protection system to extinguish an 80 kW gasoline pool fire at the battery location. For Test #2 a 3% solution of Ansulite 3x3 foam was used. During the test the foam was able to approach and contain the fire within 30 seconds. The foam was able to encroach upon and extinguish the fire within 45 seconds. The engine compartment was completely filled with foam within 60 seconds.

For Test #3 an 8% solution of ChemGuard Ecoguard F3 foam was used. During the test the foam was able to approach and contain the fire within 25 seconds. The foam was able to encroach upon and extinguish the fire within 50 seconds. The engine compartment was completely filled with foam within 60 seconds. The use of an 8% solution foam is recommended for hydrocarbon fires and produces foam better capable of extinguishing such fires.

Tests #2 and 3 demonstrate the method the Nitrogen foam uses to extinguish fires that cannot be completely cut-off from sources of fresh air. The foam initially forms a ring around the fuel pan cutting off all ventilation from inside the engine compartment. The heat from the fire causes the foam front to vaporize and release the Nitrogen gas inside. Initially the flame is strong enough to hold back the foam front and an equilibrium between the foam fill rate and the vaporization rate is achieved. As the Nitrogen is released it displaces the air above the fuel pan inside of the hood. The outside ventilation does not enable the Nitrogen gas to put out the fire by itself. However, the presence of the Nitrogen gas in the area above the fuel source does force the flame to move out from under the hood so that it is burning primarily outside of the engine compartment. This decreases the flame strength, angles the flame away from the foam front and diminishes the amount of radiant heat that is impinging directly onto the foam. The foam fill rate eventually overcomes the vaporization rate and the foam front is able to move across the fuel pan and snuff out the fire. The foam forms a seal over the top of the remaining fuel, thus preventing re-ignition.

It was also observed that after sitting undisturbed for 10 minutes within the engine compartment there was only an approximately 20% breakdown of the foam. This indicates that the foam can protect against delayed ignition and re-ignition for a long enough period of time for fire department officials to respond to the incident.

Having shown that the Nitrogen foam fire protection apparatus could accomplish its primary goal of extinguishing fires that had originated within the engine compartment, Tests #4 and 5 were conducted to observe the effectiveness of the system in two other common automobile fire situations.

Test #4 was done to observe the durability of foam to an 80 kW pool fire situated directly underneath the engine compartment. The engine compartment was filled with foam and allowed to sit for 5 minutes before the fire was ignited. The foam was able to keep the engine compartment from starting to burn independently of the pool fire for about 120 seconds. During Test #1 it was observed that the engine compartment started to burn independently of the pool fire after about 50 seconds. It can be inferred from this that the foam provides approximately one minute of protection to the engine from ignition by the fire below. This is significantly less than the goal of providing 5 minutes of protection.

Test #5 was done to determine the ability of the Nitrogen foam fire protection apparatus to extinguish a fire in a common rollover fire situation. The fire was located on the inside the hood directly underneath the engine. The foam spread across the inside of the hood and was able to rollover and extinguishes the pool fire within 60 seconds. The foam did not fill the engine compartment with foam and a large amount of the foam issued from the sides of the hood and spilled onto the ground. While the system was successful in this situation it would have been ineffective against a fire that had originated within or on top of the engine itself.

5.2 Agent System Evaluation

The NIST report reviewed in Section 1.2 introduced nine key elements to consider in the evaluation of a suppressant and a suppressant deployment system. As part of the conclusion of this thesis it seems reasonable to discuss the suppression system we have developed and tested in terms of these nine elements so that comparisons can be made to the alternate suppression strategies.

5.2.1 Vulnerability to Collision Damage

The system is constituted of a high-pressure container of about 5 liters in size and a pressure regulating valve assembly feeding the foam deployment nozzle. The container, the valve assembly and the deployment nozzle are intrinsically sturdy elements that could easily resist the collision impact with no damage. The discharge port of the deployment nozzle will be positioned between the engine block and the partition separating the engine compartment from the passenger cabin. That region of the engine compartment is not subjected to major deformation since it is located above the transmission and in general is not designed as part of the crumple zone of the automobile. The combination of location and inherent sturdiness of the proposed device suggests that there are minimal levels of vulnerability of the proposed system to collision damage. A possible configuration of the completed system is shown in Figure 67.

5.2.2 False Discharge

The activation of the device is linked to the airbag(s) deployment. Therefore, the false discharge frequency is the same associated with spontaneous airbag deployment. To re-arm the system is not particularly cumbersome and the same personnel servicing the airbag system could easily perform the procedure. The consequences of a false discharge are minimal. The foam is deployed and will degrade within a few hours leaving behind some residual solution on some of the engine compartment surface.

These residues are non-corrosive and are similar to water mixed with a mild detergent. We anticipate that most of the degraded foam will fall out of the engine compartment and only a small fraction (5 percent) of the solution will be left in the compartment. The liquid should amount to 50 mL distributed over a surface of at least 1 m^2. This would result in a layer of less than 1 mm coating the engine compartment components. As the engine is operated, the compartment heats up and the film is quickly evaporated leaving little or no trace behind. The residual film could also easily be washed away using a common garden hose and water.

5.2.3 Environmental Impact

The foam is constituted of about 2 L of solution and 850 L of Nitrogen. The gas and the water in the solution have no environmental impact. The foam concentrate is about 160 mL. The ChemGuard Ecoguard 3% F3 foam is biodegradable and should have no significant impact on the environment. As the conceptual design is further developed, different foam products should be sought to extend the operation of the system in subfreezing conditions. These foam systems may have a more significant environmental impact.

5.2.4 System Mass

The foam solution deployed is 2 L and its associated mass is 2 kg. The Nitrogen deployed is 850 L in the foam and possibly an additional 50 L with a total mass of 1 kg. The system is constitute of the pressure tank estimated at 6 kg, the pressure regulating valve assembly estimated at less than 3 kg and the foam deployment nozzle estimated at less than 1 kg. Therefore, the total weight of the empty system should be about 10 kg empty and 13 kg fully loaded. The system volume should be of the order of 5 L for the tank (4 L inside), 1 L for the regulator and 1 L for the nozzle. Therefore, the total volume of the system should be about 7 L total. Scuba tanks are available in this size that can hold a pressure of 4500 PSI. This should provide enough pressure to operate the system.

5.2.5 Hot Surfaces, Smoldering and Re-Ignition

The Nitrogen filled foam should prevent re-ignition by displacing the oxidant. Smoldering should also be limited due to lack of oxidant. The effect of hot surfaces is documented to some extent in Section 2.3.3. The foam should act to absorb some of the heat while the Nitrogen released locally by the foam should act to inert the atmosphere around the hot surface

5.2.6 Suppression Effectiveness

Nitrogen gas prevents ignition and combustion at molar fractions in excess of 86%. Nitrogen gas alone will be ineffective in preventing fires, within an engine compartment, that originate sometime after the initial release of the Nitrogen gas and re-ignition. The approach proposed in this thesis largely stops the escape of the Nitrogen through the use of the fire protection foam. The concentration of Nitrogen within the foam and in localized open areas around hot spots in the engine compartment will be equal to or higher than the 86% required. Nitrogen loss is only an issue for fires that cannot be cut off from the outside because they are adjacent to openings in the engine compartment, like around a crumpled hood. These fires can still be extinguished through the combined action of the fire protection foam and the Nitrogen gas. The localized release of Nitrogen near the fire serves to help cool the fire and reduce the oxidant concentration near the fuel source. The foam is then able to rollover and smother the flames. The combined action of the foam and the Nitrogen gas make this fire suppression approach more effective than the action of either individually.

5.2.7 Maintenance

Maintenance is limited to the valve and pressure regulator assembly to ensure proper operation. This inspection may be required with the same frequency associated with the airbag-scheduled maintenance. In addition, the Nitrogen pressure should also be monitored possibly with a minimum pressure sensor that automatically indicates the need for recharging the pressurized container.

5.2.8 Post-Fire Toxicity

Post-fire toxicity is not an issue with the present materials. The initial foam product used for testing, Ansulite 3x3, presented some toxicity issues. During full scale testing we switched to a different foam agent, ChemGuard 3% F3 Synthetic Foam. This foam product is specially formulated to present a low environmental impact. It contains no glycol ether, alkyl phenol ethoxylates or fluorine. As a result, it is 100% biodegradable while still providing the level of fire protection performance desired.

5.2.9 Cost Per Unit of Production

Assuming a cost of about $10 per kilogram the unit cost could be contained around $100 in full production. The various components are simple to manufacture and assemble since they could easily be derived from existing parts for similar applications (e.g. pressure regulators, airbags sensors, etc.).

5.3 Conclusions

This thesis provides a review of the previous work and defines the problem of suppression and re-ignition in the engine compartment of an automobile in post-crash scenarios.

The thesis describes in detail the design and testing of a novel foam generator and characterizes the optimal Nitrogen foam for this application. The proposed system is evaluated along the guidelines identified in the NIST report. The system appears to meet and exceed most of the criteria.

The thesis describes the test procedures used to design and evaluate the foam generator. Descriptions of each test scenario are laid out. Observations made and data recorded during each test are presented.

The proposed system shows significant promise. The main goal of this project was to ascertain the feasibility of controlling fires that start in the engine compartment. Tests # 2 and 3 show that the foam generator is capable of extinguishing fires in the engine compartment that would be considered challenging based upon their size and position. The difficulty is that the fire is intense enough to be able to burn off the foam as it approaches if there is not a sufficient velocity to the foam toward the fire. The positioning of the fire next to gaps in the hood provides ample fresh air for the fire and negates to a certain extent the inerting effects of the Nitrogen gas being released locally near the fire. For situations in which there are smaller fires within the engine compartment and/or the fires are located in positions not adjacent to fresh air the foam generator should be capable of extinguishing these fires more easily.

Test #4 evaluated the durability of the foam when exposed to a 5 minute, 80 kW fire that originates in a pool underneath the engine compartment. The test shows that the foam is able to protect the engine from ignition for a period of approximately 120 seconds. Further testing would need to be done to ascertain the fire size below which the foam could sustain protection. Consideration should also be given as to whether a second system should be introduced with the designed purposed of extinguishing pool fires on the ground, underneath the engine compartment. It is our understanding that Ford has developed an underbody pool fire suppression system for major fuel tank leaks. If a system like this is used together with our proposed system the durability of the foam to an underbody pool fire would become irrelevant.

Test #5 evaluated the ability of the foam generator to extinguish a fire in one specific rollover situation. The foam generator was successfully able to extinguish the fire. However, further work needs to be done to evaluate the effectiveness of the proposed system in the rollover situations the system would need to be effective in.

In conclusion, our testing indicates that the proposed system shows significant promise towards controlling and extinguishing automobile fires that originate within the engine compartment. The system, as tested, is not able to provide significant protection against pool fires that originate underneath the engine compartment and appears to be applicable to only some rollover fire scenarios. Preliminary estimates of the foam generator's final configuration indicate that it would meet reasonable weight, volume and cost constraints.

Future work should include more tests on a wider variety of fires that start within the engine compartment to ensure that the system is applicable to all scenarios. Further testing and design work needs to be done to try and extend the system to protect against pool fires that originate below the engine compartment. A full set of rollover fire scenarios needs to be developed and a system needs to be designed and tested that addresses each of these scenarios. Further work needs to be done to try and locate or develop a foam agent that would allow the system to be functional in freezing climates without compromising the effectiveness of the foam produced.

Appendix

Figure 1: Foam Generating System

Figure 2: Pressure Regulator

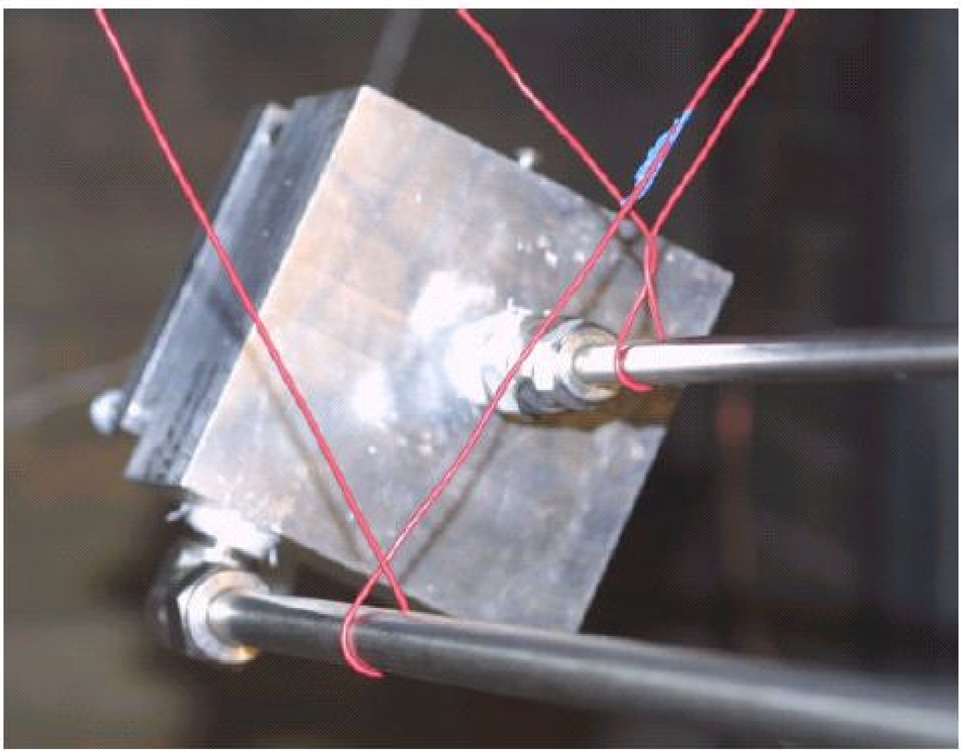


Figure 3: Foam Generator (rear view)

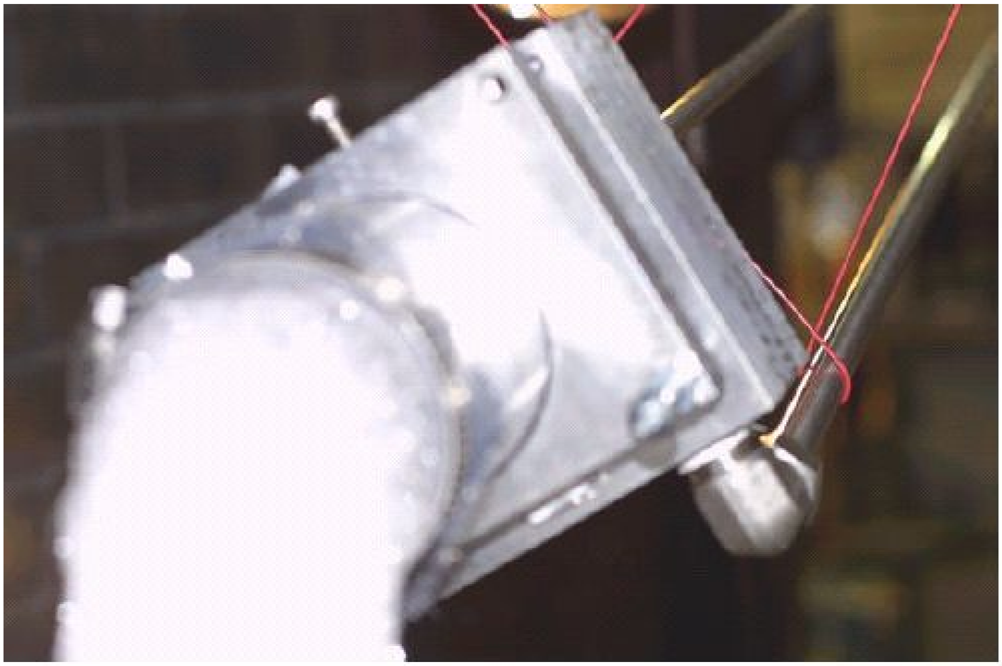


Figure 4: Foam Generator (front view, generating foam)

Figure 5: Cross-Junctions on Nitrogen Flow Lines

Figure 6: Solution Tank, Level Gauge and Connections

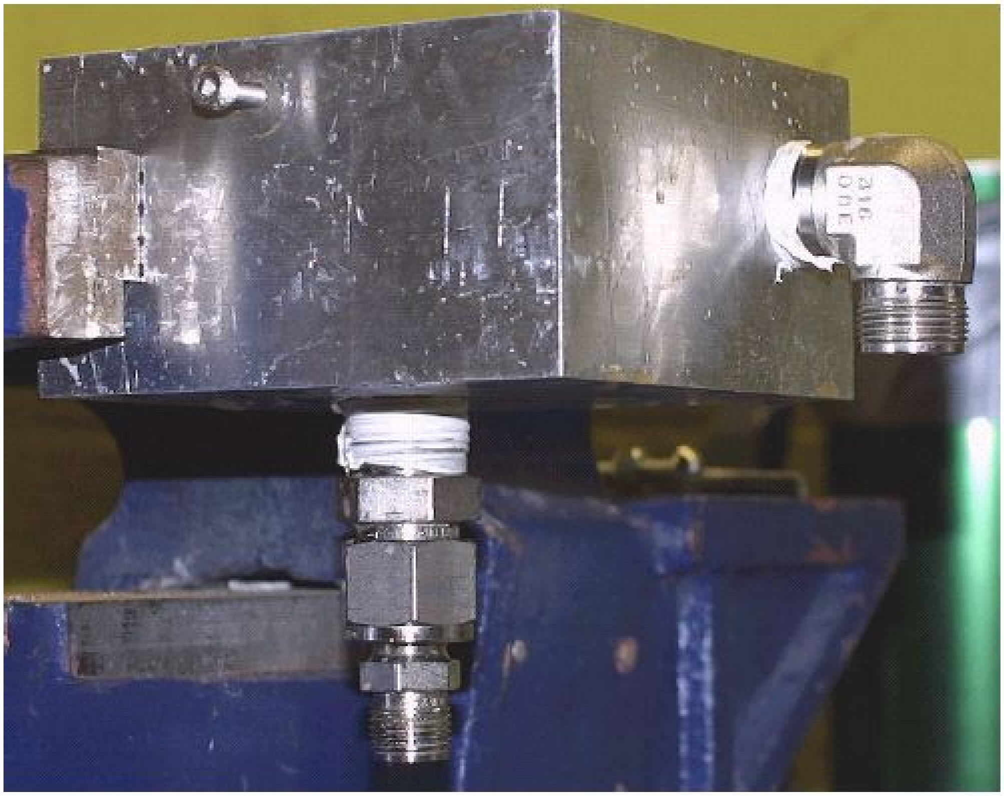


Figure 7: Foam Generator (side view)

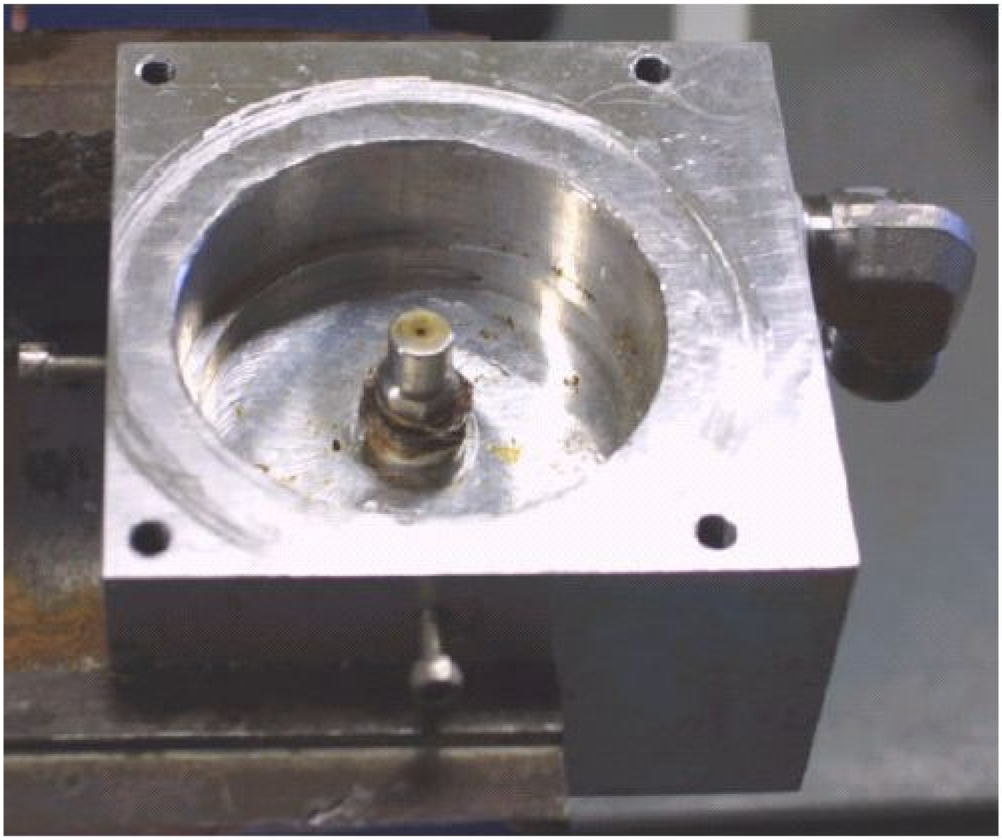


Figure 8: Foam Generator (top view) and Liquid Spray Nozzle

Figure 9: Needle Flow Valve (Whitey; BORF2)

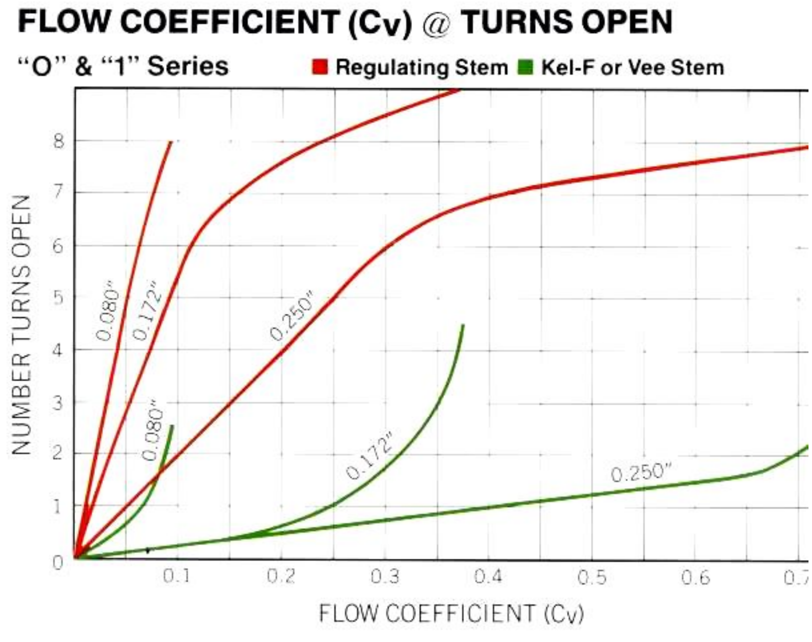


Figure 10: Cv chart for Needle Flow Valve

Figure 11: Side View of Mesh Configuration in Nozzle Pipe

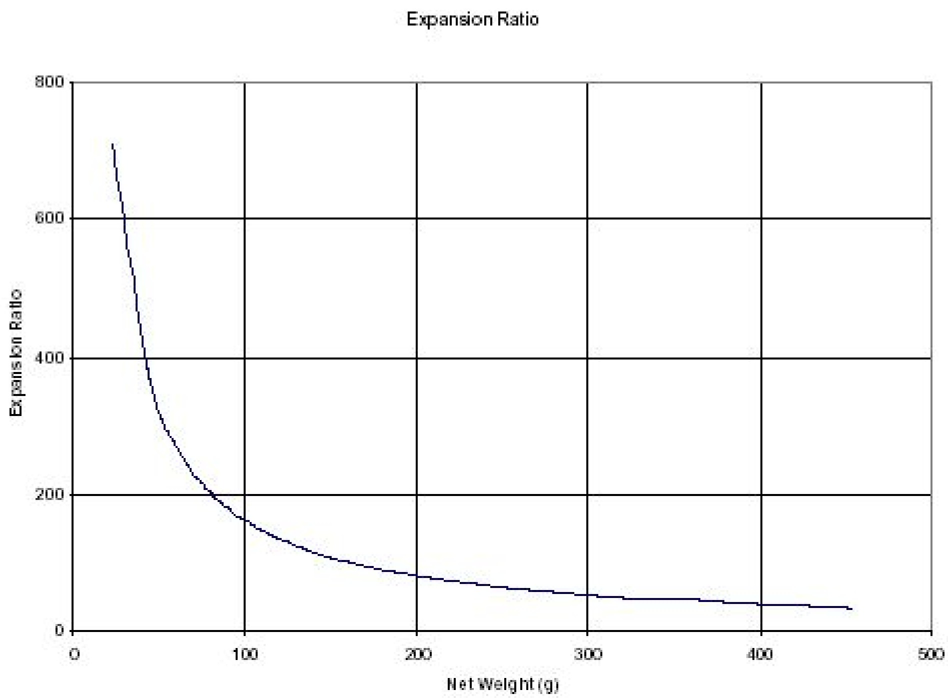


Figure 12: Plot for Determining Expansion Ratio of Foam Based on Weight

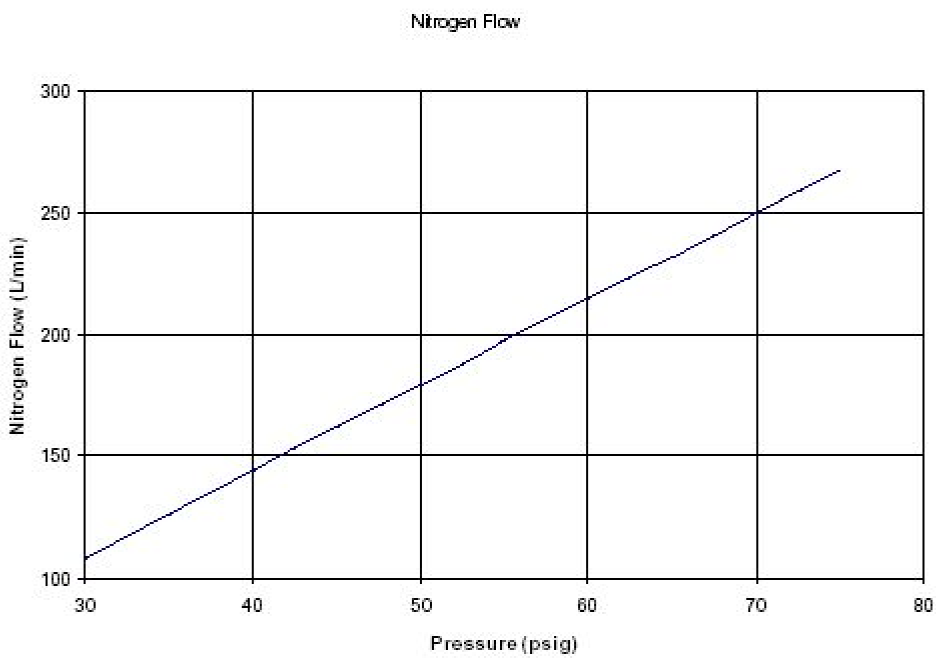


Figure 13: Nitrogen Flow Chart For 3/32-inch Orifice in Nitrogen Line at the Device

Figure 14: Inside View of Box for Modeling of Foam Flow in an Engine Compartment

Figure 15: Inside View of Foam Flow Modeling Boxes Before Connected

Figure 16: Box Set-Up #1: 11 cm² Channel Size

Figure 17: Box Set-Up #2: 8 cm² Channel Size

Figure 18: Box Set-Up #3: 5 cm^2 Channel Size

Figure 19: Box Set-Up #1 w/ 120 Expansion Ratio Foam

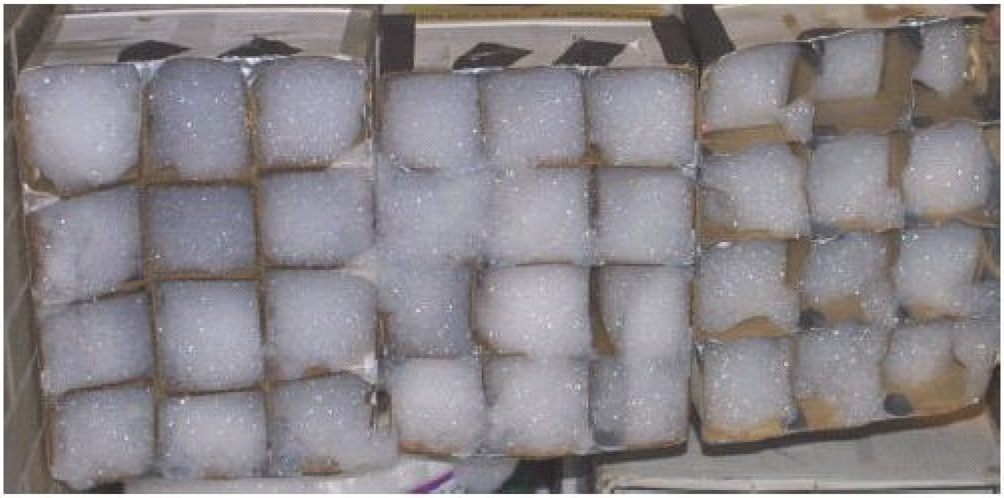


Figure 20: Box Set-Up #1 w/ 200 Expansion Ratio Foam

Figure 21: Box Set-Up #3 w/ 200 Expansion Ratio Foam

Figure 22: Foam Hang Test #1: Expansion Ration = 220, Diameter of Pipe = 0.1 m

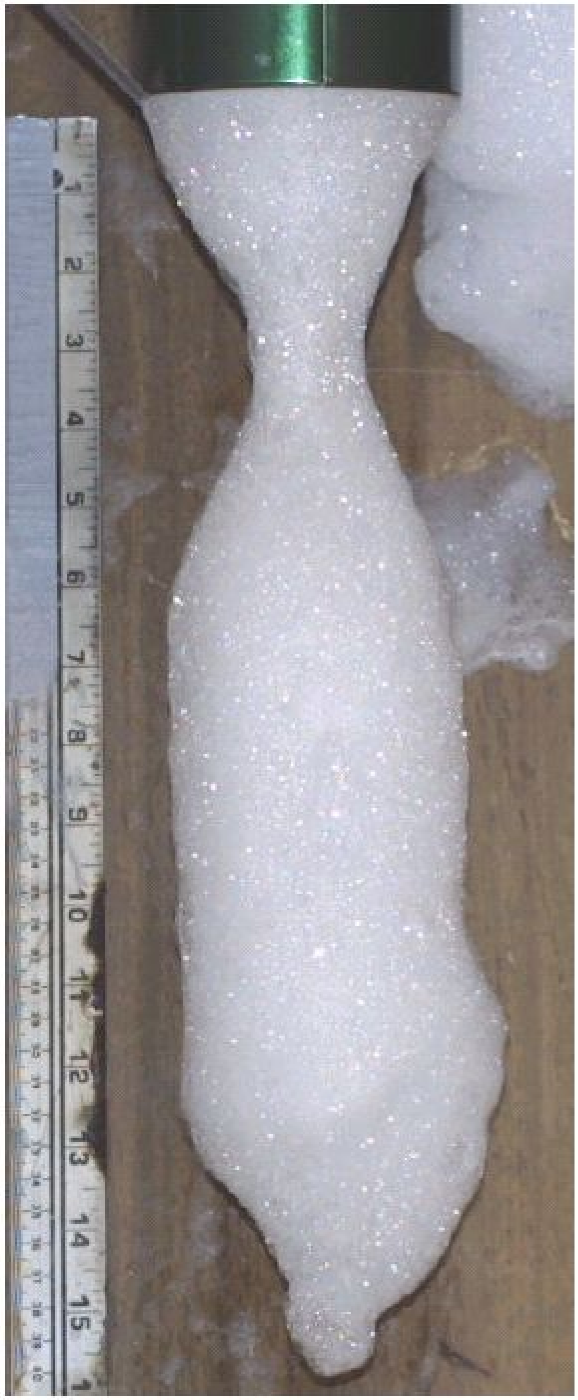


Figure 23: Foam Hang Test #2: Expansion Ration = 220, Diameter of Pipe = 0.1 m

Figure 24: Foam Hanging From Wall: Expansion Ration = 220

Figure 25: Hot Plate Set-Up

Figure 26: Hot Plate with Foam Applied: Expansion Ratio = 220

Figure 27: Hot Plate with Expansion Ratio = 220 Foam Showing Gap of 30 mm

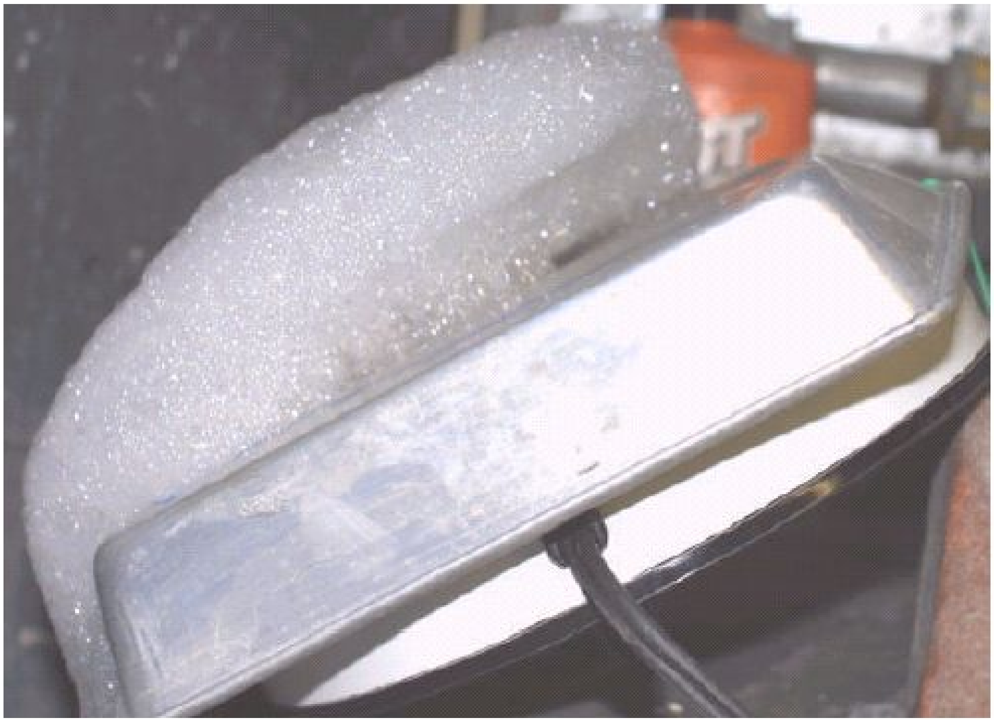


Figure 28: Hot Plate with Expansion Ratio = 220 Foam Showing Gap of 30 mm

Figure 29: Ford LTD

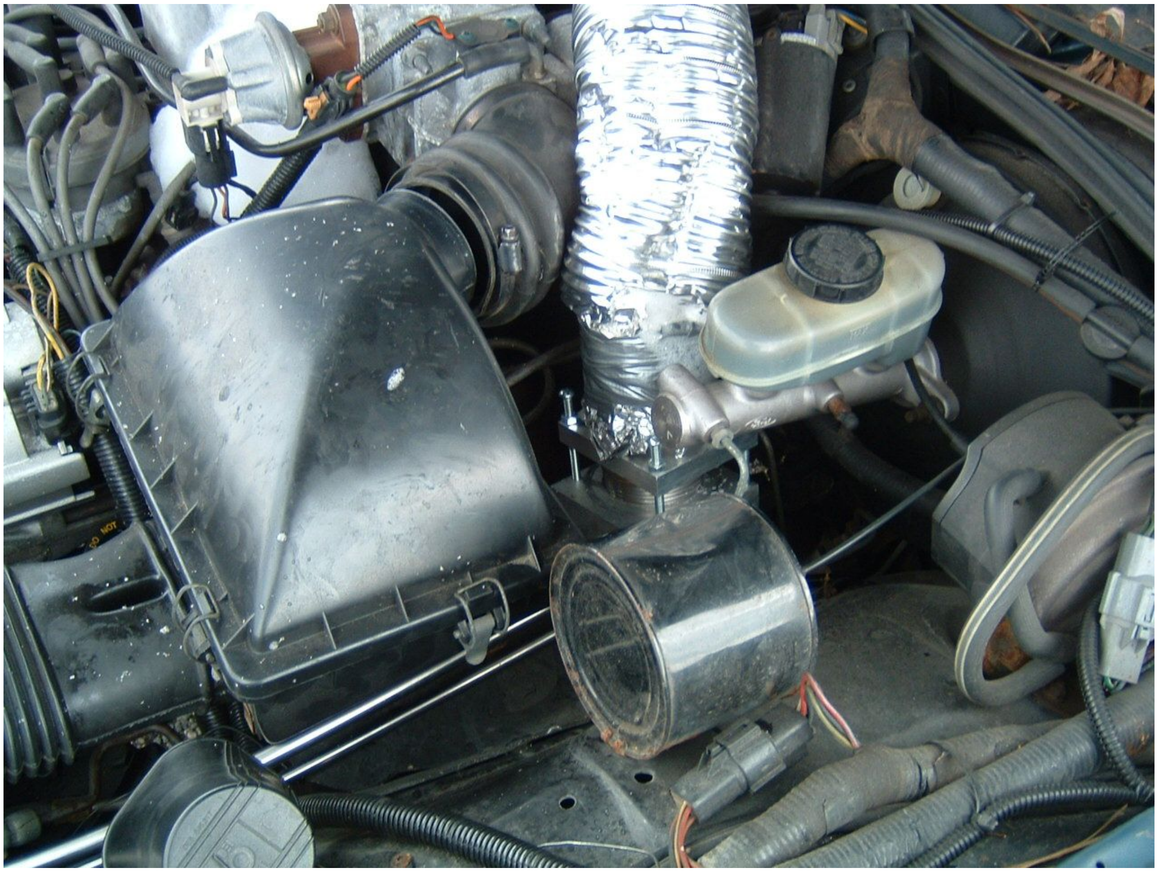


Figure 30: Position of Foam Generator Nozzle within Engine Compartment

Figure 31: Insertion Point of Stainless Steel Tubing into Ford LTD Engine Compartment through Grill, Position of Foam Generator and Position of HVAC Piping

Figure 32: Aluminum Pan in Front Right of Ford LTD Engine Compartment and Filled with Gasoline

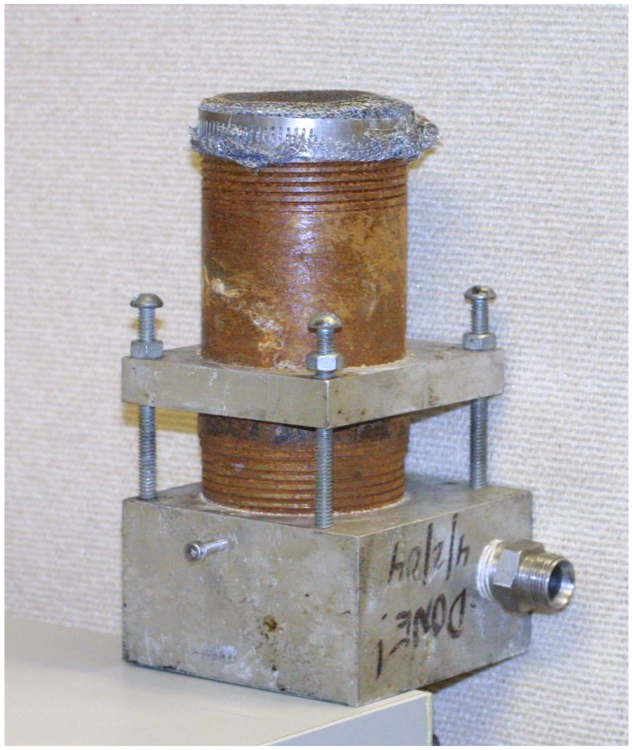


Figure 33: Foam Nozzle with Clamping Device Added to Prevent Gas Leakage

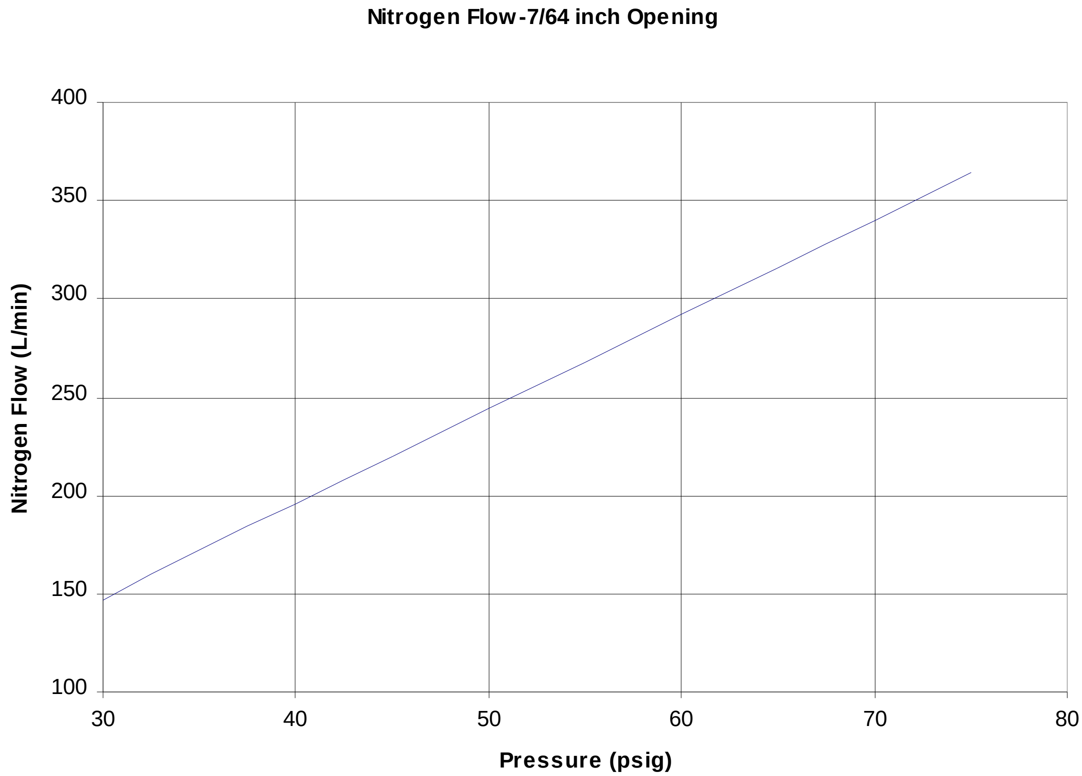


Figure 34: Nitrogen Flow Chart For 7/64-inch Opening in Nitrogen Line at the Device

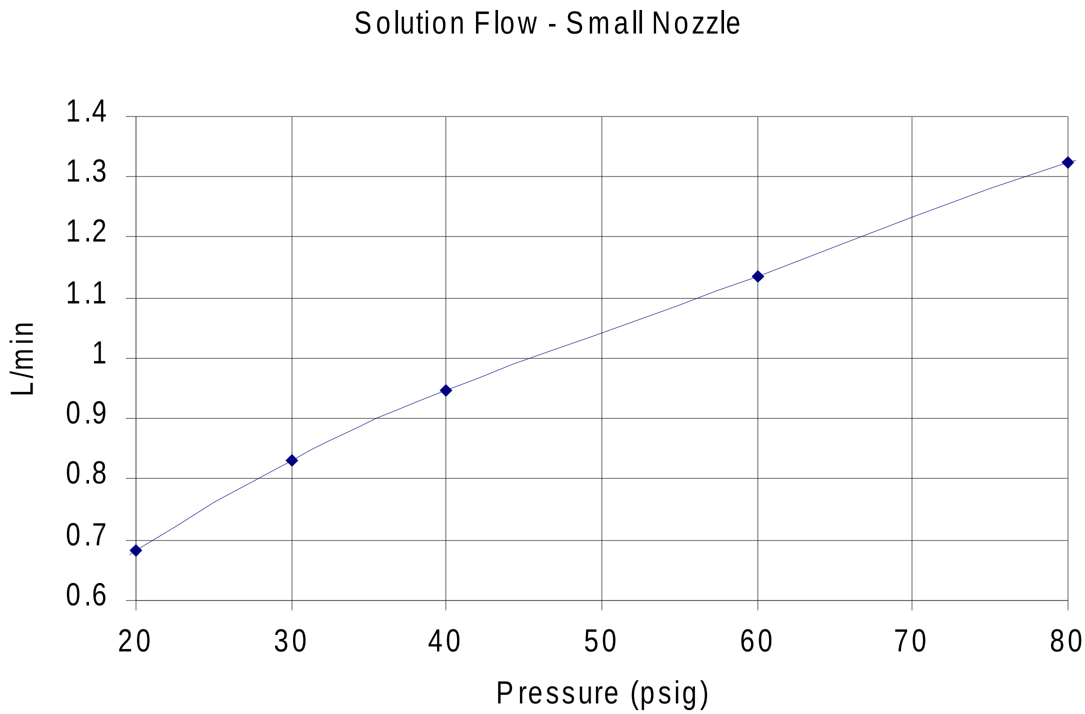


Figure 35: Solution Flow versus Pressure for BETE WL ¼ Spray Nozzle

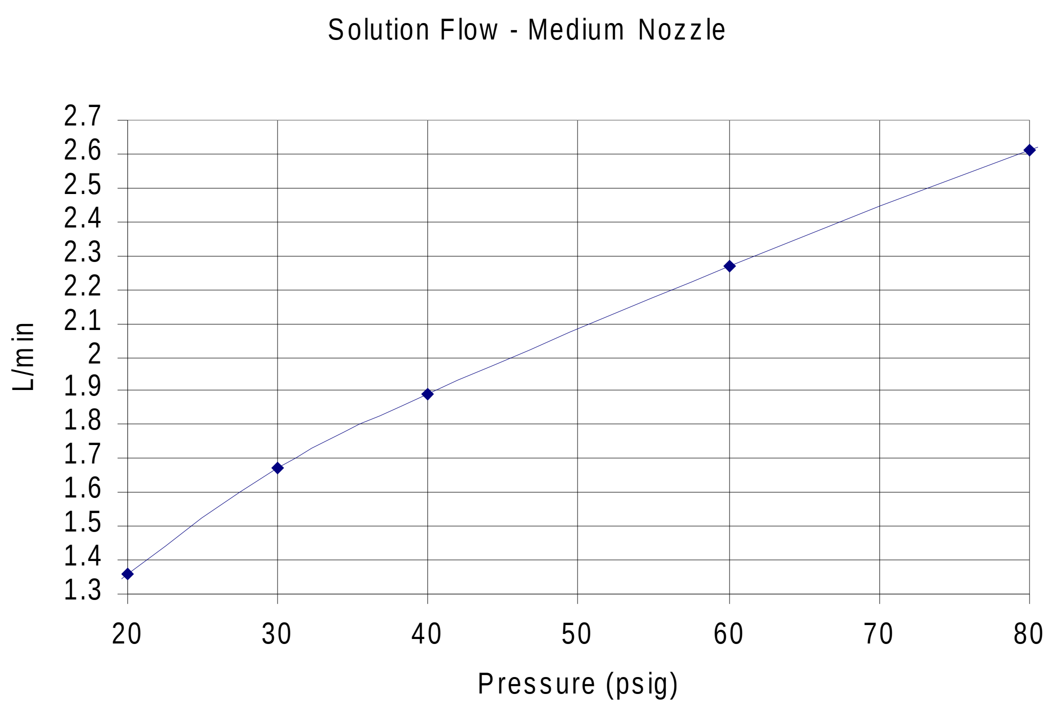


Figure 36: Solution Flow versus Pressure for BETE WL ½ Spray Nozzle

Figure 37: Burn #2 on Ford LTD: Early in Test.

Figure 38: Burn #2 on Ford LTD: Immediately Prior to Fire Being Extinguished.

Figure 39: Foam Filled Engine Compartment Showing Area Around Pan Were Fire was Located and Foam Could Not Cover

Figure 40: Close-Up View Showing Area Around Pan Were Fire was Located and Foam Could Not Cover

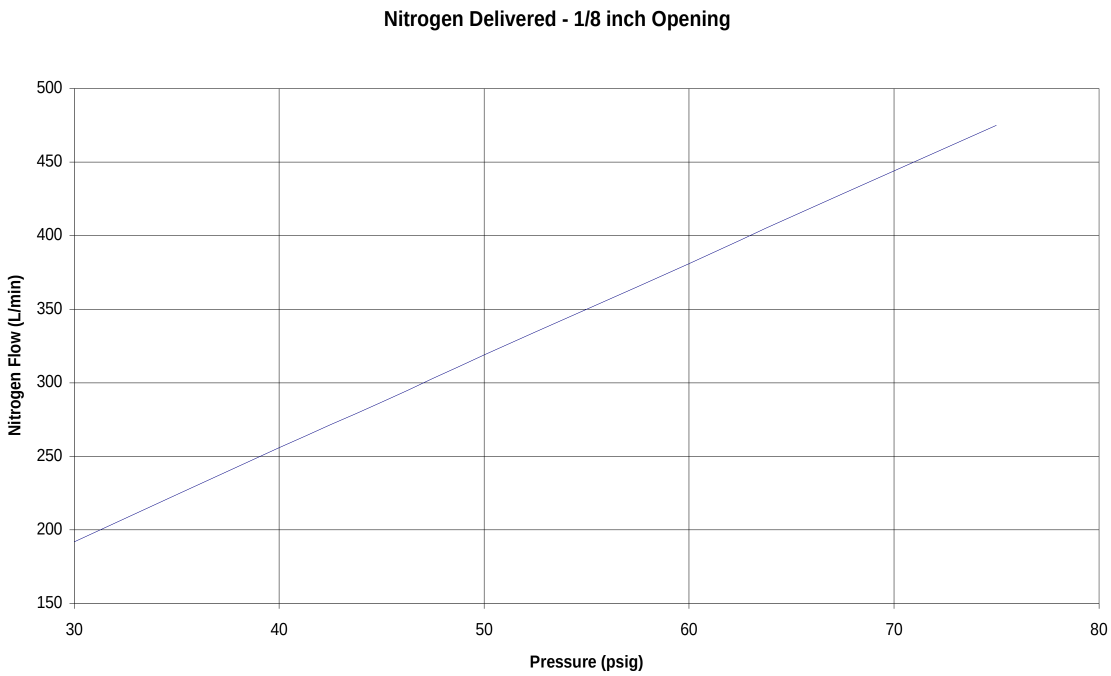
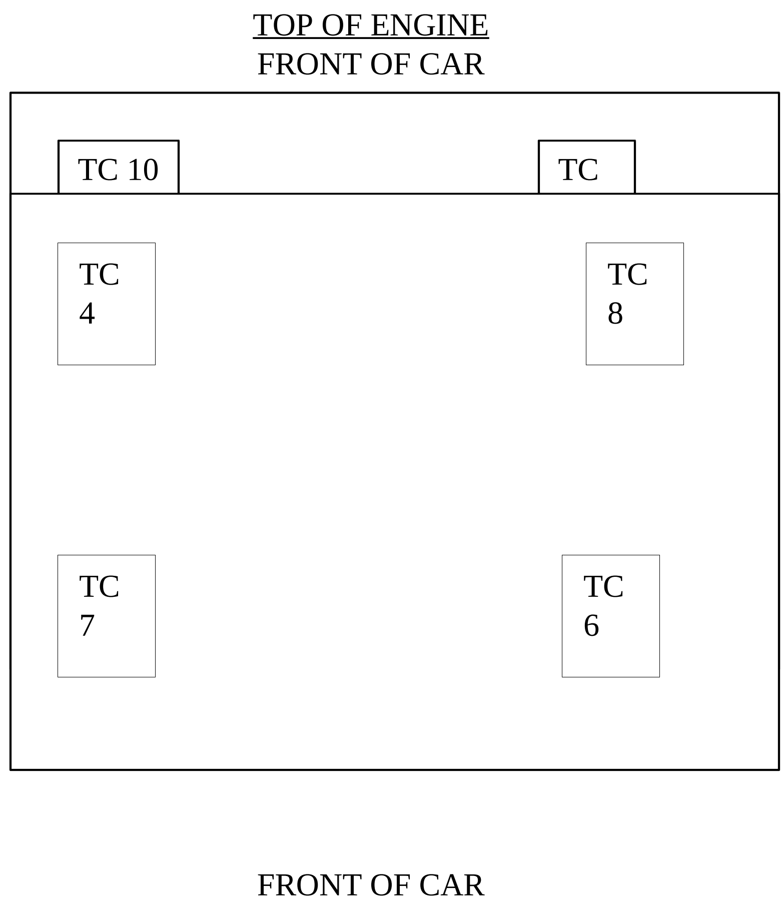


Figure 41: Flow Chart for 1/8-inch Opening on Nitrogen Line at the Device

Figure 42: Saturn Compact 4 Door Sedan

Figure 43: 0.3 m Diameter, Circular Pan, placed inside Saturn Engine Compartment



TC-2: Ambient

Figure 44: Thermocouple Placement for Free Burn of Saturn.

Figure 45: Saturn During Un-Suppressed Burn

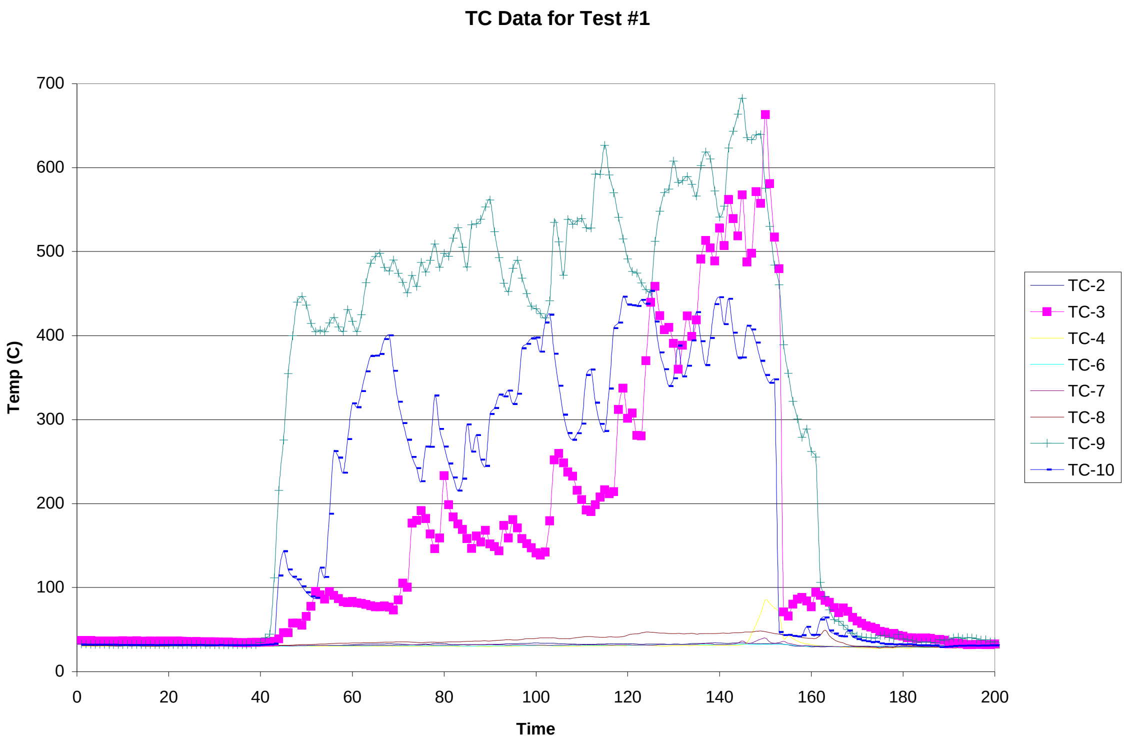


Figure 46: Thermocouple Data for Un-Suppressed Burn of Saturn

Figure 47: Chrysler Mid-Size Sedan

Figure 48: Position of Fuel Pan in Engine Compartment of Chrysler

Figure 49: Position of HVAC Piping in Engine Compartment of Chrysler (Side View)

Figure 50: Position of HVAC Piping in Engine Compartment of Chrysler (Front View)

Figure 51: Chrysler During Test, Before Foam Has Reached the Fire

Figure 52: Foam Filled Engine Compartment of Chrysler (Side View)

TOP OF ENGINE
FRONT OF CAR

Note: TC 10 is located outside of the engine compartment

TC-5: Ambient

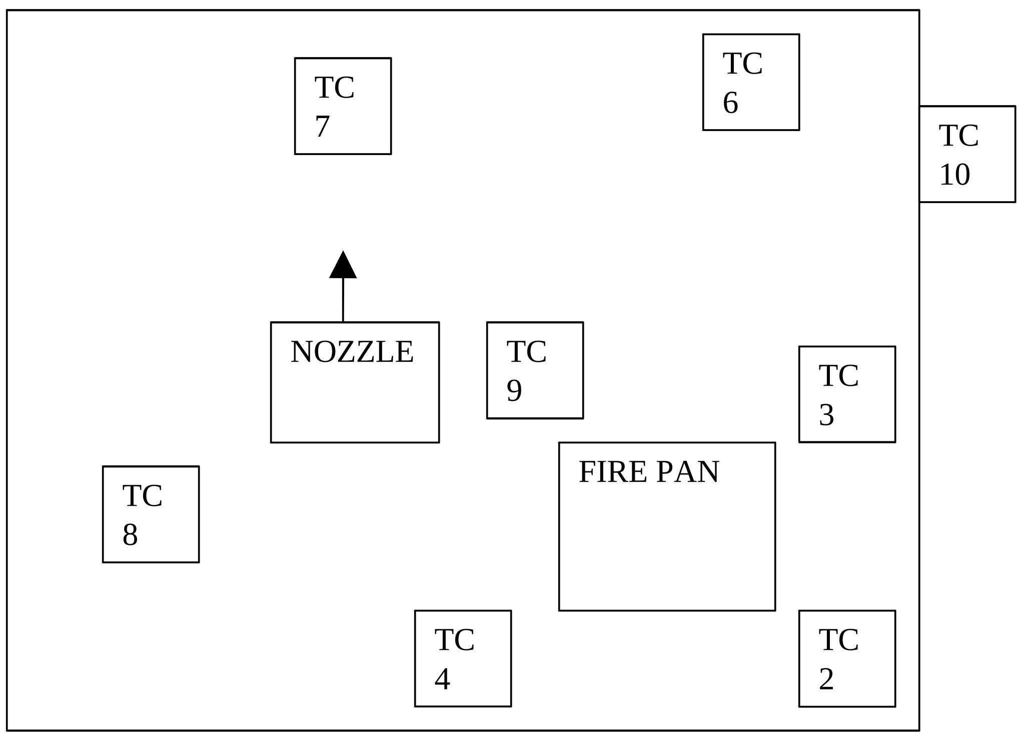


Figure 53: Arrangement of Thermocouples in Chrysler for Test #3.

Figure 54: Foam Protruding from Chrysler at Completion of Test.

Figure 55: Foam Filled Chrysler Engine Compartment

Figure 56: Foam Filled Chrysler Engine Compartment After 10 Minutes

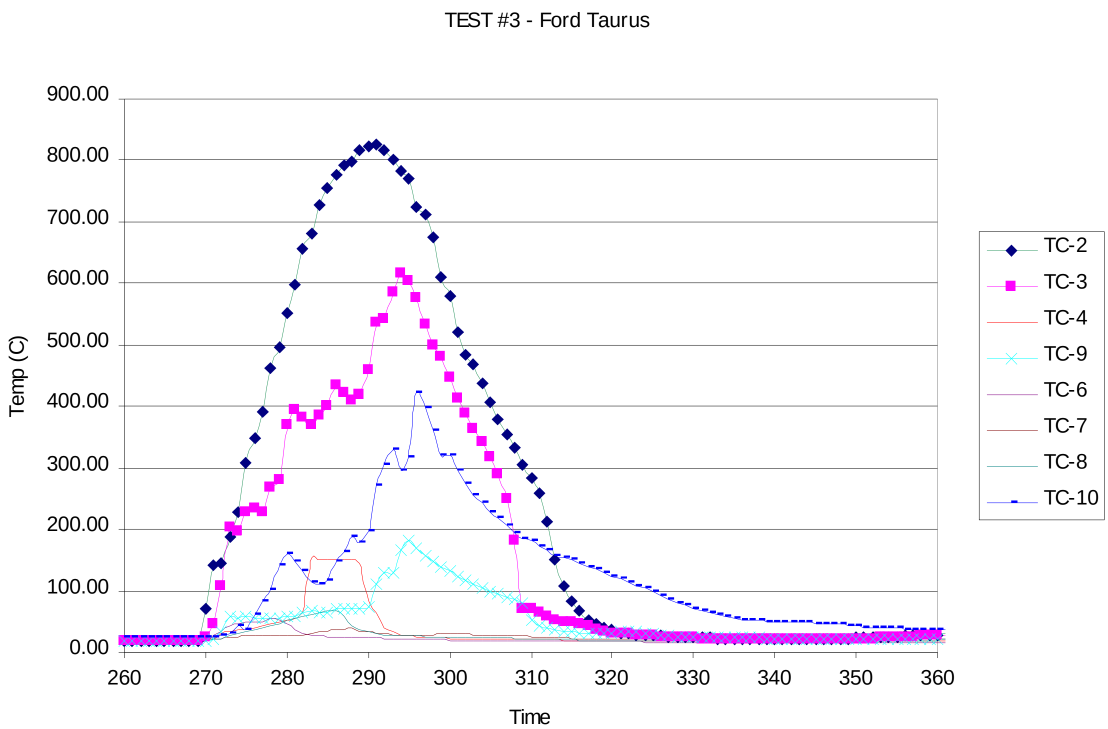
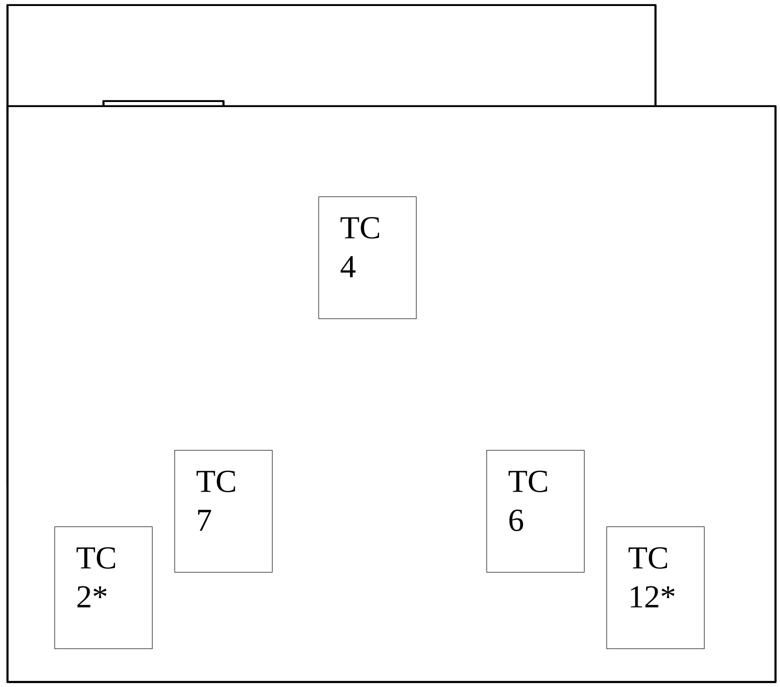


Figure 57: Thermocouple Data for Test #3 – Suppression Test on Chrysler.

TOP OF ENGINE

FRONT OF CAR



FRONT OF CAR

*Note: TC 4, 6 and 7 are located in the middle of the engine compartment within the engine. TC 2 and 12 are located on the bottom of the engine within the wheel wells.

TC 9: Ambient

Figure 58: Arrangement of Thermocouples in Chevy Cavalier for Test #4

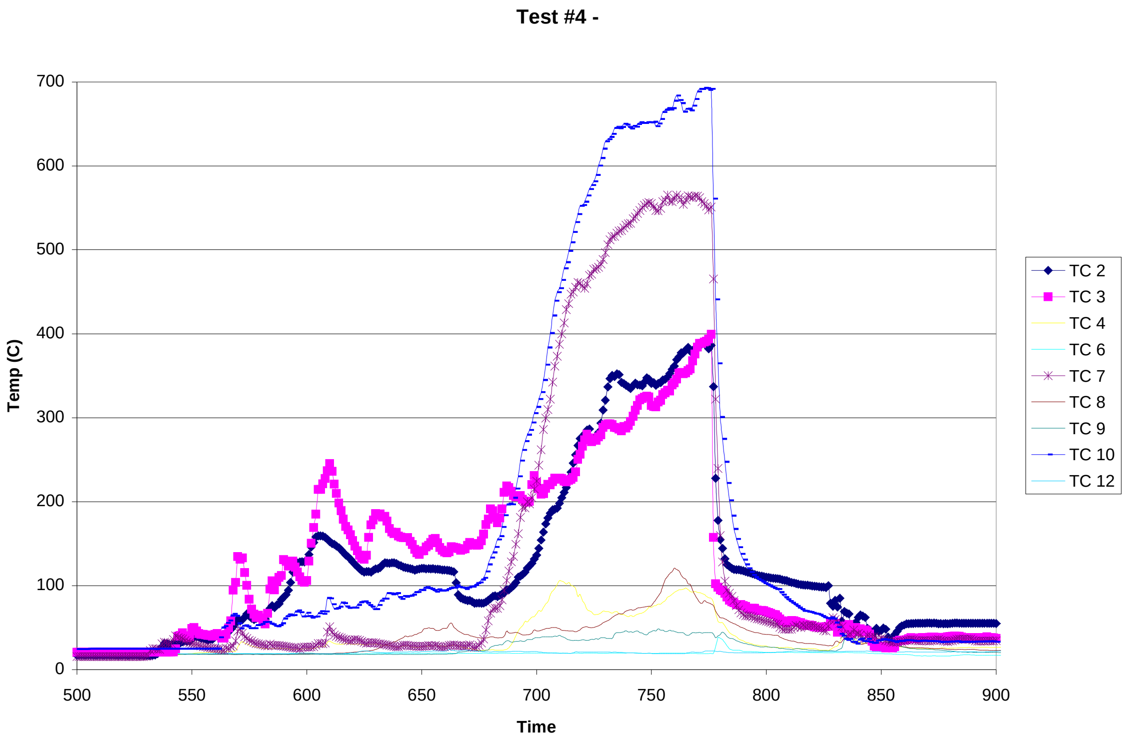
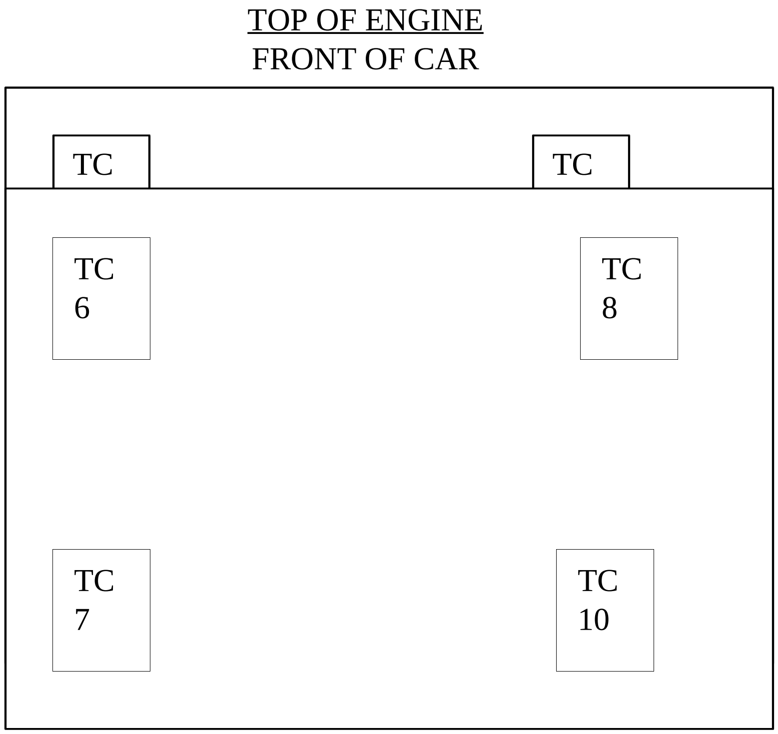


Figure 59: Thermocouple Data for Test #4

Figure 60: Mercedes Flipped onto its Top (Side View).

Figure 61: Mercedes Flipped onto its Top (Front/Top View).

Figure 62: Position of Pan on Inside of Hood.



FRONT OF CAR

Note: This is how TC’s appear when car has been flipped. The Bottom of the Engine Compartment is in the air above the Top of the Engine Compartment.

Figure 63: Arrangement of Thermocouples in Mercedes for Test #5.

Figure 64: During Rollover Test, After Foam has Moved Over the Top of the Fire Pan.

Figure 65: Movement of Foam from Sides of Hood.

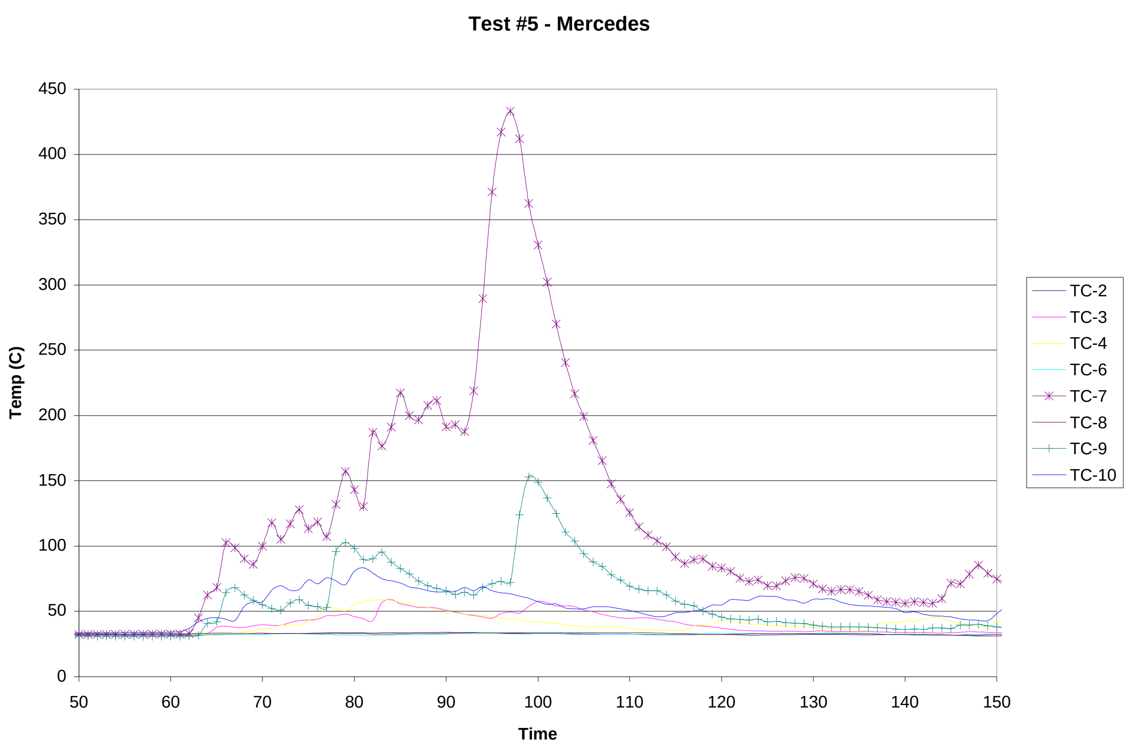


Figure 66: Thermocouple Data for Test #5 – Rollover Suppression Test on Mercedes.

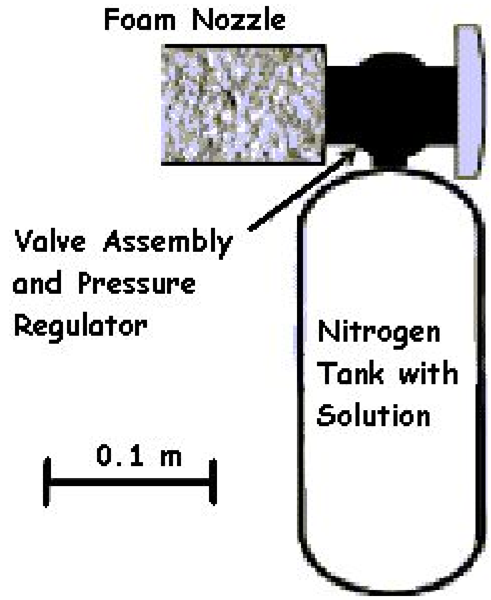


Figure 67: Integrated System Sketch of Possible Configuration of Working Foam Generator System

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