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Evaluation of the Ignition Hazard Posed by Onboard Refueling Vapor Recovery Canisters

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ABSTRACT

ORVR (Onboard Refueling Vapor Recovery) canisters trap vapors during normal operations of a vehicle's engine, and during refueling. This study evaluates the relative risks involved should a canister rupture in a crash. A canister impactor was developed to simulate real-world impacts and to evaluate the canisters' rupture characteristics. Numerous performance aspects of canisters were evaluated: the energy required to rupture a canister; the spread of carbon particles following rupture; the ease of ignition of vapor-laden particles; the vapor concentration in the area of ruptured, vapor-laden canisters; and the potential of crashes to rupture and ignite canisters. Results from these five items were combined into a risk analysis.

INTRODUCTION

Evaporative emissions control has evolved to become more effective as evaporative emission standards have become more stringent. On-board refueling vapor recovery (ORVR) systems are now the norm for passenger cars and they will be phased in for lightweight trucks by the 2002 model year. These systems are quite effective in reducing the amount of hydrocarbons released to the atmosphere. We sought to evaluate the relative risk of ignition-after-collision for the ORVR system and the enhanced evaporative emissions system it replaces.

To make this evaluation, several types of data are required. First, the energy to rupture a canister and the resulting distribution of carbon are required. Next, possible ignition sources must be identified, along with their effectiveness at causing ignition. Finally, in the event of canister rupture, the volume in which a combustible mixture will form must be determined. Using the data, along with the existing data on highway collisions, we performed a comparative risk analysis.

EXPERIMENTAL STUDY OF CANISTER RUPTURE

The purpose of this testing was to study the amount of energy necessary to rupture a canister, and study the spilling and spreading of the carbon grains after rupture. For safety and simplicity, the tests were conducted with virgin canisters. We used Delphi 2100cc canisters in this work. These injection molded nylon canisters use activated carbon which provides a working capacity of 15BWC (15 g butane/100cc). The main body of the canister is roughly box-shaped with dimensions of 9cm X 15cm X 22cm tall. The bottom is attached by vibration welding. The energy required to rupture the canister was evaluated for the bottom, the wide face, and the narrow face.

CANISTER RUPTURE DEVICE AND TESTING SPECIFICATIONS

The rupture device was designed so the impactor would generate impact speeds similar to those that might exist in actual vehicle crashes; the consensus being that impact speed influences carbon dispersal. Accordingly, the impactor was designed to provide a constant speed of approximately 48 kph (30 mph) for all impact energies.

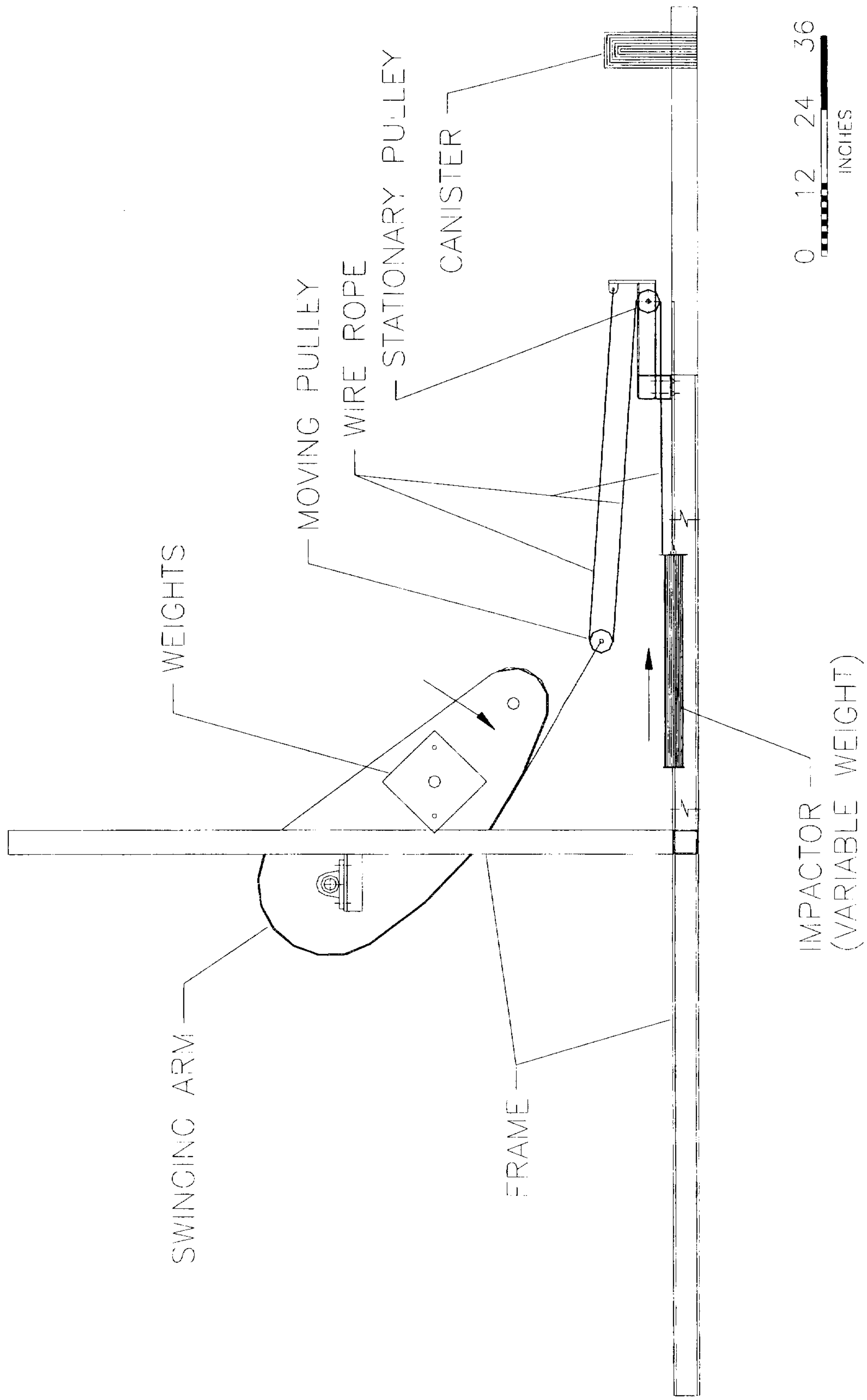

Figure 1: Schematic of Canister Rupture Device

Figure 1 is a side view schematic of the impactor illustrating how the impactor operates. The impactor is accelerated to speed by the action of a swing arm, which is a cam-shaped aluminum plate. Weights can be added to both the arm and impactor to increase the energy of the impact while maintaining a constant impact speed. The plate pivots about a shaft. The plate is raised prior to impact and a steel cable is wrapped around the plate, fitting in a groove cut along its perimeter. The cable connects to the impactor through a series of pulleys, providing a 4:1 speed multiplication between the speeds of the center-of-gravity of the swinging weights and the impactor. Thus, 48 kph is achieved with a relatively short 0.6 m (2-ft) swing arm radius (radius of the center of mass) and the whole device fits inside a room. To achieve 48 kph with a normal pendulum would require a swing height of 9 m (30 feet).

The impactor travels horizontally using six low-friction Teflon bearings built into the impactor. The impactor is moved to the rear of the rails before the rupture device is triggered. Near the end of its travel the impactor disconnects from the cable and hits the canister. Since the canisters in vehicles will not be mounted rigidly, the canisters were strapped to a 3 mm (1/8 inch) backing plate, which was judged to be the most rigid surface to which they would be attached in a vehicle. The energy levels listed in subsequent paragraphs refer to the energy of the striking impactor, not the actual energy absorbed by the canister.

The impactor itself is a 0.075 m (3 inch) diameter aluminum tube. The impactor has a 0.125 m (5 inch) radius semispherical head at the impact end (front) and hardware for attaching various ballast at the rear. The impactor test weights ranged from 2.19 to 18.2 kg (4.82 to 40 lb). The speed of the impactor was measured for each test, and was generally 90-94% of the theoretical (zero friction) speed (approximately 48 kph).

CANISTER RUPTURE RESULTS

The minimum energy required to break a canister and spill at least some carbon was measured in the preliminary testing phase. The minimum energy in each of the three directions was 175 N-m (129 ft-lb) for the wide side, 212 N-m (157 ft-lbs) for the narrow side, and 107 N-m (79 ft-lb) for the bottom. A complication arose in that there was considerable variation between canisters in the minimum energy to break a canister. Some unloaded (no gasoline vapor) canisters withstood impacts at 4 times the minimum energy. For loaded canisters, some withstood 6 times the minimum energy. There may be considerable variation between canisters, but the testing also suggests that the temperature of the plastic material may affect the breaking strength, with warm canisters being stronger. Many plastics show an increase in ductility as temperature increases, which would allow the carbon particles to absorb more energy before the plastic ruptured. Lower breaking energies were typically observed in the winter months with a partially heated room, while higher breaking energies were achieved with the room warm, and the highest break energies were with the canisters warm from a recent fast-loading procedure. No canisters were tested at very low (sub-freezing) temperatures.

Table 1: Summary of Canister Impact Tests

Canister/Test Number	Side Tested	Energy N-m (ft-lbs.)	E/E_{min}	Carbon Scatter
5	Wide	938 (693)	5.37	Yes
7	Narrow	864 (638)	4.06	Yes
8	Narrow	844 (623)	3.96	Yes
9	Narrow	844 (623)	3.96	No
10	Wide	343 (253)	1.96	No
11	Wide	727 (537)	4.16	Yes
13	Bottom	217 (160)	2.03	Yes
14	Bottom	217 (160)	2.03	Slight
15	Bottom	211 (156)	1.98	Yes
16	Bottom	437 (323)	4.09	Yes
17	Bottom	450 (332)	4.20	Yes
18	Bottom	437 (323)	4.09	Yes
19	Wide	1067 (788)	6.11	Yes
20	Wide	1067 (788)	6.11	Yes
21	Wide	1067 (788)	6.11	Yes
22	Narrow	1334 (985)	6.26	Yes
23	Narrow	1334 (985)	6.26	Yes
24	Narrow	1297 (958)	6.10	Yes

Table 2: Summary of Carbon Scatter Measurement Tests					
Canister/Test Number	Side Tested	Most Carbon in One Tray (grams)	Total Carbon in Trays (gram)	Total Carbon Outside Trays (grams)	Total Carbon Spilled (grams)
5/d	Wide	5.7	26.1	Negligible	26.1
7/c	Narrow	132.8	300.0	Negligible	300.0
8/c	Narrow	91.7	136.0	Negligible	136.0
11/c	Wide	228.9	340.3	Negligible	340.3
13	Bottom	78.5	147.6	Negligible	147.6
14	Bottom	8.2	8.2	Negligible	8.2
15	Bottom	6.5	16.0	Negligible	16.0
16	Bottom	51.3	62.6	Negligible	62.6
17	Bottom	25.3	52.1	Negligible	52.1
18	Bottom	48.0	94.9	Negligible	94.9
19	Wide	165.5	303.9	8.5	312.4
20	Wide	171.5	341.7	Negligible	341.7
21	Wide	60.2	130.7	Negligible	130.7
22	Narrow	54.6	198.0	42.0	240.0
23	Narrow	85.0	267.8	29.5	297.3
24	Narrow	31.1	277.0	52.7	329.7

To break the canisters, they were hit with 2 times the minimum energy. If breakage did not occur, the canister was hit with 3, then 4, then 5, then 6 times the minimum energy, with each hit being on the opposite side from the previous hit. If the canister broke but did not spill carbon, record that as a break with no spillage, and discontinue testing on that canister. On tests in which a canister did not crack, no change in the integrity of the canister was observed.

When testing the bottoms of the canisters, all canisters broke and spilled carbon at twice the minimum energy. Canister bottoms were also tested at 4 times the minimum energy, mostly to study the carbon spill. Table 1 summarizes the results of canister testing.

Carbon Scatter

The scatter of the charcoal was measured by using a series of plastic trays, each 135 mm (5.3 inches) square. The trays were arranged in a grid to determine the pattern of carbon scatter. In all cases the vast majority of the spilled carbon fell into the trays adjacent to the canister. The scatter outside the trays was weighed as a unit. In the higher energy tests the carbon dispersal was wider, that is, a larger fraction of the spilled carbon was thrown beyond the adjacent trays. Tabular results for the carbon scatter are shown in Table 2.

There appears to be no strong correlation between the energy level and the amount spilled, although the general trend is that higher energy levels resulted in greater carbon spillage. It is likely that in a vehicle, post-impact motions of the vehicle would have a large influence on the amount of carbon spilled from the ruptured canister.

CANISTER LOADING SPECIFICATIONS AND PROCEDURES

During its use in a vehicle as well as in this test, the activated carbon in a canister will absorb certain heavy hydrocarbon vapors which can not be purged under reasonable purging conditions. This mass of heavy hydrocarbons is sometimes known as the "boot", or "heel". When working with laden canisters it is appropriate to first prepare or break-in the canisters by adding a mass of hydrocarbons to represent the "boot".

Each canister was put through a series of adsorption-desorption cycles. In each cycle the canister was loaded using 2.8 l/min of air bubbled through 25°C gasoline, until 2g breakthrough was achieved; it was then purged with room air for 30 minutes at 23 l/min (about 300 bed volumes). Final weight (at the completion of a cycle) increased rapidly at first, and converged toward an asymptote in later cycles. Generally 6 cycles were sufficient to achieve a stable final canister weight.

After preparing the canisters, two canister loading protocols were used during testing. The two procedures simulate two important scenarios in which vapors are captured by the canister, refueling and diurnal emissions. Because hydrocarbon adsorption is an exothermic process, a significant amount of heat will build up during rapid loading, while temperatures will be much lower if the hydrocarbons are slowly fed into the canister. At higher temperatures, the vapor is released much more easily and the capacity will be lower. The protocols are:

Fast Fill - To Simulate Canister Loading During Refueling

- Fill Until 2 gram Breakthrough Level *
- 75°F, 9 RVP Gasoline
- 10 gal/minute Pump Rate, Nominal 22 Gallon Fill
- Test Loaded Canister within 0-10 Minutes of Filling
- Canister Warm from Loading

The "2 gram breakthrough" mentioned is simply the amount of vapor passed through the canister indicating carbon saturation.

Slow Fill - To Simulate Canister Loading During Extended Periods of Slow Vapor Gain

- So-called '1.5x Enhanced' Fill
- 75°F, 9 RVP Gasoline
- 4 gal/minute Pump Rate, Nominal 22 Gallon Fill
- Soak One Hour
- Repeat Until 175 g Gain
- Soak One Hour
- Test Canister within 4 Hours of Loading
- Canister Nominally at Ambient Temperature

To load the canister in either of the above methods, fuel of the appropriate RVP and temperature was passed from a drum to a large tank at the appropriate rate. Air laden with vapor from the tank was passed to the canister.

INVESTIGATION OF POSSIBLE IGNITION SOURCES

The objective of this phase of the testing was to identify and test possible ignition sources that might be present in the vicinity of a canister at the time of an actual accident. The following four ignition sources were identified as being the most likely to be present:

1. Open flame
2. Hot metal such as a taillight or headlight filament
3. 12 V electrical spark
4. Mechanical spark

The fast-load method (described in the previous section) caused the carbon to heat up more and thereby provided a worst case condition. The test protocol for the fast-load canister testing was to test the canister within ten minutes of loading.

Source No. 1 - Open Flame

A 20 ml sample of carbon was placed on a flat base in a pile about 8 cm in diameter. A small flame (about 12 mm long) was placed at the level of the base and brought inward from 150 mm in 25 mm increments. The flame was held in position for 10 seconds before moving inward. This was performed three times with new 20 ml samples of carbon for each test. Ignition occurred at 100 mm, 50 mm and 100 mm in three consecutive tests.

Source No. 2 - Hot Metal

Taillight filaments were used as the hot metal. For each test, three bulbs were prepared such that their brake light filaments could be separately energized. A 20 ml sample of carbon was placed in a pile approximately 8 cm in diameter. The bulbs were placed at varying distances from the carbon and were energized in order beginning with the furthest from the carbon. After a filament failed (typically after 6 seconds or so) the system was observed for about 2 seconds. Assuming no ignition had occurred, the next filament was energized. It was previously determined that the most effective vertical location of an ignition source was on the plane of the base of the carbon pile. Filaments were placed on the base surface at varying distances from the carbon pile. The distance from the edge of the pile ranged from 12 to 50 mm. A car battery producing 12.9 volts was used to energize the filaments.

For the first test, no ignition occurred at 50 mm. The next setting was 25 mm where ignition occurred. For the second test, with a fresh 20 ml of carbon, the increments were decreased so that filaments were placed at 50, 37.5, and 25 mm. Again, ignition did not occur until the 25 mm filament was energized.

Source No. 3 - Electrical spark

The test setup included carbon steel posts and a carbon steel hand-held electrode. The posts were connected to the negative pole of a 12 V car battery and the moving electrode was connected to the positive pole. The initial voltage was 12.9 V. A 20 ml pile of carbon was placed so that the posts were about 25, 50, and 62.2 mm from the pile. The sparks were made by brushing the hand-held electrode across the posts, beginning with the one farthest from the pile. If no ignition occurred after repeated sparking, the next closest post was used. This was repeated with a fresh 20 ml sample of carbon.

In the first test, ignition occurred at the 50 mm distance. In the second test, ignition occurred at the 25 mm post after about 10 seconds of sparking.

Source No. 4 - Mechanical spark

A flint/steel torch lighter (hand squeeze) was used to create the mechanical sparks. A 20 ml sample of carbon was placed on a flat surface in a pile about 8 cm in diameter. Locations for the spark source were marked on the surface at 25, 50, 75 and 100 mm. Sparks were

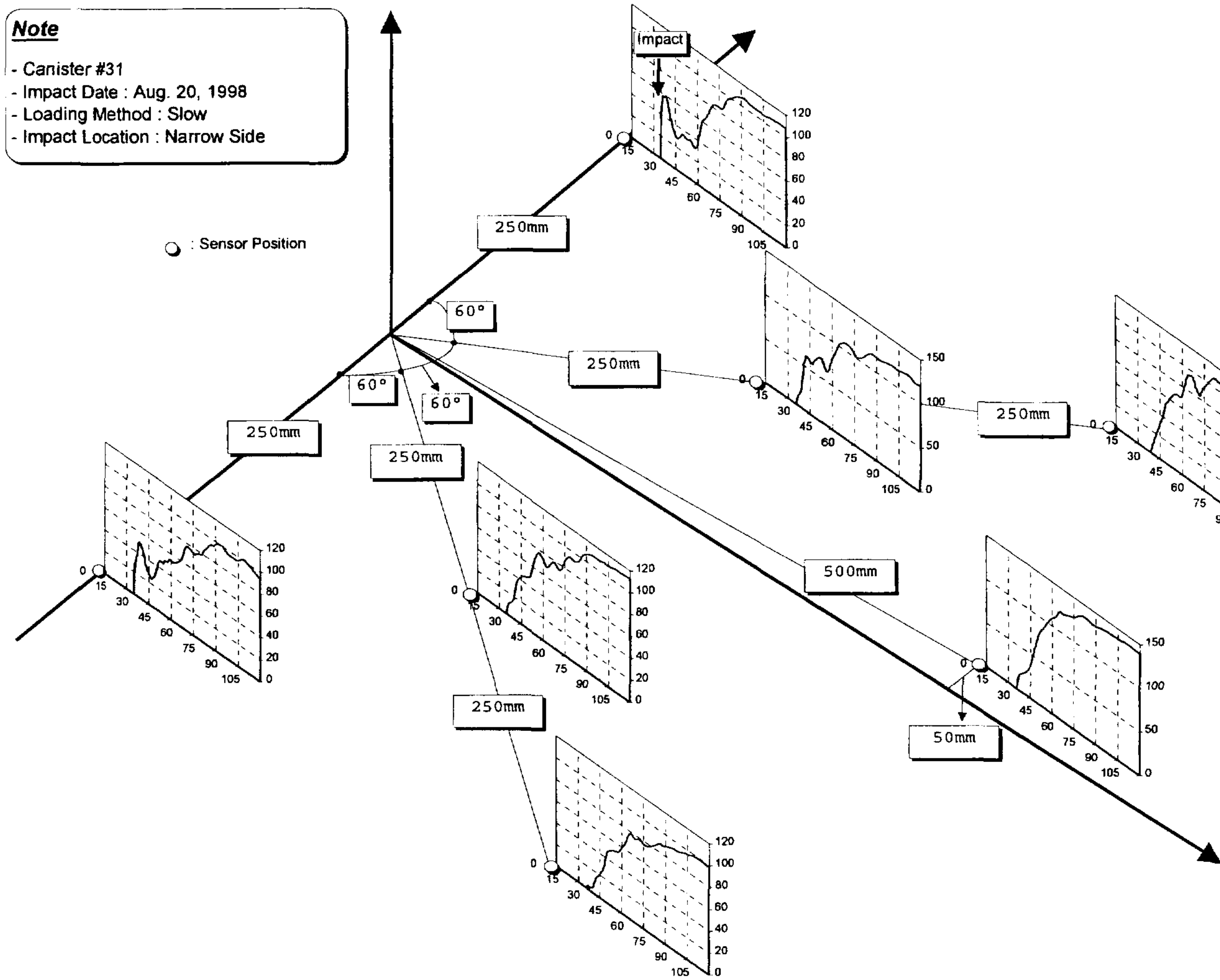

Figure 2: Vapor Concentration Sensor Positions

created at the 100 mm location and, if no ignition occurred after 10 seconds, the process was repeated at the next closest location. The sparks traveled a significant distance from the source, and some actually touched the pile of carbon while they were still red hot. In three successive tests, ignition occurred at 75mm, 50mm and 75mm.

IGNITION OF UNRUPTURED CANISTERS

A canister was prepared, loaded with vapor, and placed on its narrow side on the concrete floor of the canister test laboratory. A burning candle was used as the ignition source. When the flame reached a distance of approximately 75 mm (3 inches) from the opening, ignition of gases exiting the canister occurred in the form of a small 20 mm long flame coming from the opening. The flame stayed burning after the candle was removed. The flames were left burning until the canister tube opening began to melt and burn. These tests demonstrated that vapors emanating from laden canisters are flammable and able to burn long enough to cause the canister material to ignite. Under their normal configuration, these canister tube openings are not open to the atmosphere.

MEASUREMENT OF VAPOR CONCENTRATION AFTER CANISTER RUPTURE

The vapor concentration levels in the vicinity of the ruptured canisters were measured using Figaro Model 822 organic solvent vapor sensors. The vapor sensors were supplied with 5 volt inputs, and circuitry was designed and built so the sensors' maximum output voltage would correspond to roughly 120-140% of the lower flammability limit (LFL). The sensors were calibrated daily against a Bacharach Sentinel 44 LFL meter. As configured, the sensors saturate in the range of 120-140% LFL. Sensor saturation did occur in some tests.

Seven vapor concentration sensors were used to make measurements during the actual rupture tests. Preliminary testing showed that, since gasoline vapor is much heavier than air, the vapor stayed close to the ground. Figure 2 shows the sensor positions used for testing. To prevent the sensors from becoming covered with carbon, the sensors were raised to 20 mm off the

Table 3: Summary of Vapor Concentration Measurement Test Configurations					
Canister Number	**Loading Method**	**Impact Location**	**Peak Concentration (% LFL)**	**Time above %100 (seconds)**	**Comments**
20	Fast	Narrow Side	115*	>50**	
21	Fast	Narrow Side	115*	>50**	
22	Fast	Narrow Side	115*	>35**	
23	Slow	Wide Side	130*	>90**	
30	Slow	Wide Side	110*	>50**	
31	Slow	Narrow Side	120*	>55**	
24	Slow	Bottom	35	0	
25	Fast	Bottom	50	0	
27	Fast	Bottom	50	0	
32	Fast	Wide Side	50	0	Room doors open
28	Fast	Narrow Side	100	5	Room doors open

*Sensor reached saturation, actual peak concentration could be much higher.
**Concentration above 100% when data collection terminated.

floor in their final positions.

Table 3 lists the configurations used for the vapor concentration tests. Tests were done using both the slow and fast canister fill methods and using impacts to all three canister impact positions; wide side, narrow side, and bottom. The last two tests were run with doors open at each end of the canister test laboratory to allow a slight breeze to flow across the test area. The wind speeds were measured using an anemometer and they are recorded in Table 3.

Canisters 20, 21, and 22 were all narrow side impacts using the fast fill method. Ruptures from these three tests resulted in fairly widespread dispersal of carbon in the region of the sensors. Most sensor recordings for all three of these tests indicate LFL levels of over 100%, indicating that the vapor concentration near the floor in the entire region of the sensors was at a combustible level. Some of the sensors did not quite reach 100% LFL, generally in areas where little carbon was spilled. In some instances, for the sensors farthest away from the canisters, the LFL level rise times were delayed relative to the closer sensors. This was judged to be due to a propagating "cloud" of vapor. This too was a function of the amount of carbon in the vicinity of the sensors. The results of these three tests also demonstrate that the process used is reasonably repeatable.

No conclusive differences were noted between the slow and fast fill methods, rather the measured LFL levels are a function of amount of carbon spilled and the distance from the carbon to the sensor.

The tests of canisters 24, 25, and 27, which were all bottom impacts, resulted in minor ruptures with small amounts of spilled carbon. None of the sensors recorded LFL levels above 50% during these tests. In general, the sensors reached their peak LFL levels about 30-60 seconds after the impacts of canisters 24, 25, and 27. This gives an indication of the rate and amount of vapor flow from broken canisters with a small amount of spilled carbon. After 2½-3 minutes the sensor recordings dropped to near zero as the vapors dispersed into the laboratory.

All but 2 of the concentration measurements were done in an unventilated room with little air circulation. In 2 of the tests doors in opposite ends of the test room were left open. The rupture of canister 28 resulted in about 300 grams of spilled carbon. Only one of the sensors reached an LFL level above 100%, and only for a brief period of time. None of the sensors reached 60% after the rupture of canister 32, which spilled a moderate amount of carbon. Based on the amount of carbon spilled, had the doors been closed, LFL levels of over 100% at most sensor positions would be expected. This indicates that a breeze could significantly reduce the ground level vapor concentrations in the vicinity of a ruptured canister loaded with fully vapor-laden carbon. The air speed in the area of canisters was measured using a hot-wire anemometer. Air speeds were always below 60 m/min (200 ft/min) and were usually only a fraction of this.

VEHICLE CRASH TESTS

For the crash tests it was necessary to have ignition sources mounted on the target vehicle in the vicinity of the canister that would survive the impact from the collision with the moving barrier, and continue to be active for two minutes after impact. The taillight filaments previously tested survived for only about six seconds, and using any of the other three ignition sources during the crash tests appeared to be problematic. As a surrogate to any of the likely ignition sources identified, automotive cigarette lighters were used as ignition sources during the crash tests.

Two crash tests were run to test the rupture and ignition propensity of vapor loaded rear mounted ORVR canisters. The tests were designed to represent two plausible real world crash scenarios yet maximize the possibility of ignition. Both tests used General Motors H-body vehicles (containing an ORVR canister) as the stationary target vehicles and the FMVSS 214 deformable movable barrier as the impacting vehicle. The side impact test vehicle was a 1997 Buick LeSabre and the moving barrier was positioned to strike the vehicle at an angle of 41° with a speed of 70 kph and with initial contact being the foremost corner of the barrier in line with the canister. The rear impact test used a 1997 Pontiac Bonneville SSE with a moving barrier speed of 85 kph and an impact zone of 50% overlap of the rear of the vehicle. The canisters used for tests were loaded using the slow fill method.

The side impact test was executed as planned, with impact occurring at the proper orientation and position at a speed of 69.5 kph. The metal band holding the canister in place broke during this test, and as a result the canister became detached from the vehicle.

In the rear impact test, at a distance of about 6 m (20 ft.) from impact the skate connecting the moving barrier to the pull cable failed causing the barrier to prematurely disengage from the pull cable. The barrier pulled slightly to the right and reduced the impact speed to approximately 74 kpm. About 40-45% of the rear of the vehicle was impacted by the moving barrier.

The canister did not break during the rear impact test. Although the rear of the vehicle was significantly crushed, the crush zone did not extend in front of the rear axle. There was no noticeable damage to the canister or its surrounding area. In spite of the test problems, this crash test represented a fairly severe rear impact and the fact that the canister did not break was not unexpected based on the extent of vehicle damage. Significantly more energy would be required to cause deformation into the canister region.

RISK ANALYSIS

The following relative risk analysis is intended to be an estimate only, and is intended to be an upper bound of the risks associated with carbon canisters. Potential sources of error in the risk analysis are also mentioned. Separate risk analyses were performed for front- and rear-mounted canisters.

The number of canister-caused fires per year can be evaluated using the following formula:

$$N_{fires} = \sum_i N_i A_i B \qquad (1)$$

where:

N_{fires} = number of canister-caused fires per year

N_i = number of collisions per year in one of the Collision Damage Classification (CDC) coded accidents that is in the region of the canister

A_i = probability of this collision causing the canister to break open and spill carbon

B = the probability of ignition if carbon is spilled

Each index "*i*" above refers to a certain Collision Damage Classification (CDC) damage level code given in [1]. This code is a 7-column combination of numbers and letters which gives an indication of the location on the vehicle and severity of a collision. The third column in this code is the general area of damage: front, rear, left, right, etc. Column 7 gives an indication of the depth of the residual crush. Columns 3 and 7 together can be used to convert a CDC to an approximate damage depth, and can be used in the above formula.

For the rear-mounted ORVR canisters only, collisions to the side of the vehicle and at the rear of the vehicle are considered. With the canister mounted ahead of the rear axle, few rear collisions will produce damage severe enough to reach the canister. There are 9 damage levels to be considered in rear impacts.

For front-mounted canisters, collisions need to be considered from the front and from the side but at the front of the vehicle. Thus, 17 different CDC coded accidents need to be considered. Front-mounted canisters are mounted in the area behind one of the headlights.

The N_i's in Equation (1), the estimated number of accidents per year with a CDC in one of the categories, were provided on request by the National Highway Traffic Safety Administration.

Factor A is the likelihood that the canister will break and spill carbon, and will be a number between 0 and 1. It was assumed that for damage level 1, A was zero. It was also assumed that A could be no larger than 0.95 to reflect that even in the most severe accident there is a chance the canister will not rupture.

Factor A was estimated by producing a probability-of-rupture curve as a function of impactor energy. The data came from the 45 impactor tests where either the wide or narrow sides of the canister were struck. Canister rupture is expected to be more likely at the higher energy levels, but there is considerable scatter in the data.

It was assumed that the amount of energy absorbed by the canister was equal to the amount of energy per unit volume absorbed by the crush zone. For a given damage level, one can calculate the energy per unit volume of the crush zone, and relate this to a probability of canister rupture.

The total energy E (in in-lbs) absorbed in a collision can be estimated from [1].

$$E = L\left(\frac{K_A}{2}(C+C) + \frac{K_B}{6}(3C^2) + \frac{K_A{}^2}{2K_B}\right) \quad (2)$$

where:

C is the average damage depth in inches

L is the length of the damage zone in inches

K_A and K_B are the stiffness parameters, which will vary from vehicle to vehicle, and be different for the front and sides of the vehicle.

K_A and K_B values are available for the front, rear, and sides of vehicles, and for a number of vehicle sizes. [2]. Average values of K_A and K_B for the front and side were used. For the frontal impacts, frontal values of K_A and K_B were used, and they were:

K_A = 62,000 N-m/m^2 (349 in-lb/in^2)
K_B = 38,400 N-m/m^2 (54.0 in-lb/in^3)

For the impacts to the side of the front, frontal values were again used, since the side values typically are for the door area, and vehicles are much stiffer at the front end. For the impacts to the rear side (rear-mounted canister) side values of K_A and K_B were used. These were:

K_A = 25,200 N-m/m^2 (142 in-lb/in^2)
K_B = 36,700 N-m/m^2 (51.6 in-lb/in^3)

The average crush depth, C, can be assumed to be about 0.75 of the maximum value, which can be related to the damage level from the CDC.

The volume of the crush zone will be approximately LCh, where h (the average height of the crush zone) is about 0.55 m (22 inches). In calculating the crush energy per unit volume of the crush zone, L drops out of the equation, and the formula for crush energy per unit volume is:

$$E/vol = \frac{K_A}{h} + \frac{3K_B C_{max}}{8h} + \frac{2K_A{}^2}{3K_B h}\frac{1}{C_{max}} \quad (3)$$

For each damage level from the CDC code a C_{max} is calculated, a crush energy per unit volume is calculated from Equation (3), and a probability of rupture, A_i, is estimated.

Factor B in Eq. (1) is the probability of ignition once carbon is spilled. B is assumed to vary with the amount of vapor in the canister and would also vary with the system mass. In this relative risk analysis there is no need to analyze how B varies with the mass since the same canister is considered in both locations. Extension of this formula to a general canister would require an analysis of how both A and B vary with the physical parameters of each canister.

Factor B was calculated from the following methodology. The state of fill for activated carbon may be calculated based on assumptions about temperature, drive cycle, and fuel composition. We used proprietary GM computer software to determine the vapor composition in the canister over the fill-and-use cycle for a tank of fuel. GM used this software to size evaporative emissions systems. The software incorporates basic physical chemistry principles and experimental data into a single model. The model and its output have been validated by a decade of use. The results are expected to be accurate to at least 10% of the value calculated, but typically results are better than 5% for systems such as the one at hand.

All calculations were based on the carbon and canisters actually tested in the experimental section of this project. Summer simulations were made using 10.1 RVP fuel, spring simulations were made using 12.0 RVP fuel, and winter simulations were made using 15.7 RVP fuel. All fuels were 10 volume percent ethanol blends at or near the appropriate ASTM volatility limit (including the ethanol RVP waiver) this will maximize vapor production. The software accounts for fuel weathering (including diurnal warming and cooling) on a chemical species basis.

In all cases an equilibrium level of "heel" or "boot" (strongly bound hydrocarbons) was assumed prior to fill up. A 68-liter tank was filled at 570 cc/s (18-gallon tank at 9 gal/min). In the calculation, each day the vehicle experienced an 11.1° C diurnal warming cycle with a drive cycle at either end; in each drive cycle 2.33% of a full tank was consumed. The low and high diurnal temperatures used for the simulations were -12.2 and -1.1° C (10 and 30° F) in winter, 10 and 21.2° C (50 and 68° F) in spring, and 21.2 and 32.2° C (70 and 90° F) in summer. After the second drive cycle a 6-hour rest period at the high temperature level occurred. During this period, the vapor in the canister partially redistributes

Table 4: Risk Analysis Results Rear-Mounted Canister				
Damage Level (*i*)	**Accidents per Year in US (N_i)**	**Probability of Rupture (A_i)**	**Probability of Ignition (*B*)**	**Number of Fires per Year in US (N_{fires})**
2	12736	0.118	0.00024	0.359
3	8639	0.118	0.00024	0.243
4	614	0.19	0.00024	0.028
5	66	0.32	0.00024	0.005
6	11	0.71	0.00024	0.002
7	8	0.87	0.00024	0.002
8	104	0.95	0.00024	0.024
9	169	0.95	0.00024	0.039
			Total	**0.702**

itself. A third drive cycle ensued; it was also calculated at the high temperature point. Finally, air was sucked into the system at night, as the system returned to the low temperature level. This pattern was continued until the vehicle's fuel tank was ¼ full; at that point it was refueled. Fuel and air temperatures during refueling were assumed to be 14.4 and 21.1° C (58 and 70° F) in spring, 21.2 and 32.2° C (70 and 90° F) in summer, and +1.7 and -1.1° C (35 and 30° F) in winter.

Calculated vapor concentrations were always highest during the first high-temperature drive cycle following a refill. By the second day, vapor storage had dropped to roughly 10% of the removable vapor stored directly after refueling. After refueling, combustible vapor concentrations were generally only present in the canister during the first high-temperature drive cycle (after the diurnal warming had injected fresh vapor into the canister). In winter simulations even this cycle contained a non-combustible mixture after the second day.

It was then assumed that the chance of ignition was proportional to the volume of the ignitable vapor cloud, and that the size of the ignitable vapor cloud was proportional to the amount of vapor in the carbon, once the carbon was spilled.

The mathematical formula for *B* for a given season of the year is:

$$B = \frac{1}{T}\int_0^T \frac{m}{170}\frac{V_{ig,170}}{V_{source}}\,dt \qquad (4)$$

where:

m = the mass of vapor in the canister (in addition to the boot) in grams

$V_{ig,170}$ = the volume of the ignitable cloud when there are 170 grams of vapor in the canister

V_{source} = volume of a vehicle where ignition sources are assumed to be present

T = drive time between refueling cycles

As described in an earlier section, a number of canisters were broken that were filled with approximately 170 grams of vapor in addition to the boot. Using vapor concentration data from these tests, the volume of the ignitable vapor cloud, when there are 170 g of vapor in the canister, was estimated to be 0.0393 m^3 (1.4 ft^3).

Data on the likelihood of an ignition source being present is limited. [3] shows that an ignition source is likely in the front end of the vehicle (with electrical system damage reported in 8 of the 12 staged collisions analyzed). Very few accidents result in fire (about 1%). Clearly, few accidents result in the correct combination of spilled fuel and ignitable vapors, but it is unclear whether the relative rarity of fires indicates a lack of fuel or a lack of ignition sources.

It was assumed that in any collision there would be one ignition source within the volume of the body of the vehicle (neglecting roof and tires). The average volume of the body of a vehicle was assumed to be about 5.05 m^3 (178 ft^3). The integration in Eq. (4) can be performed, yielding a value of *B*. Averaging all the data and considering different seasons gives the yearly average for *B* as 0.00024.

A number of assumptions limit the risk analysis. The most important of these is that wind effects were largely

Table 5: Risk Analysis Results Front-Mounted Canisters				
Frontal Impacts				
Damage Level (*i*)	**Accidents per Year in US (N_i)**	**Probability of Rupture (A_i)**	**Probability of Ignition (*B*)**	**Number of Fires per Year in US (N_{fires})**
2	171403	0.63	0.00024	25.7
3	43469	0.95	0.00024	9.91
4	8021	0.95	0.00024	1.83
5	3609	0.95	0.00024	0.823
6	3424	0.95	0.00024	0.781
7	1903	0.95	0.00024	0.433
8	1828	0.95	0.00024	0.416
9	2036	0.95	0.00024	0.464
Side Impacts				
Damage Level (*i*)	**Accidents per Year in US (N_i)**	**Probability of Rupture (A_i)**	**Probability of Ignition (*B*)**	**Number of Fires per Year in US (N_{fires})**
2	31858	0.33	0.00024	2.52
3	26596	0.50	0.00024	3.19
4	3572	0.70	0.00024	0.600
5	866	0.88	0.00024	0.182
6	29	0.95	0.00024	0.007
7	29	0.95	0.00024	0.007
8	35	0.95	0.00024	0.008
9	41	0.95	0.00024	0.009
			Total	**46.9**

ignored. Another factor is that the vapor cloud will typically be very close to the ground, while the ignition sources will be higher. Another assumption is that in many severe collisions, fuel is spilled from the fuel lines and tank, which will form a much greater source of ignition than any spilled carbon.

The results of the risk analysis are provided in Tables 4 and 5 for the rear-mounted and front-mounted canisters, respectively. The tables reflect the fact that front-mounted canisters are vulnerable to impacts from both the front and side, while the rear-mounted canisters are vulnerable only from the side.

To get the accidents per year column above, the total number of accidents for both left and right sides of the vehicle was taken and divided by two.

For a given damage level, the number of fires per year (Column 5 in Tables 8 and 9) is the product of the number of accidents per year (Column 2) times the probability of rupture (Column 3) times the probability of ignition (Column 4). The totals listed in Tables 4 and 5 represent the estimated total number of canister-caused fires per year in the United States for rear-mounted and front-mounted canisters, respectively.

CONCLUSIONS

It is possible for a canister to be ruptured, though the energy levels required to do this appear to be higher than one would typically see in an accident. If an ORVR canister ruptures soon after refueling, it is possible that the spilled carbon particles would emit enough vapor to form an ignitable cloud, however, this cloud is rather small, stays close to the ground due to the density of gasoline vapors, and is easily dispersed by wind.

Within the limits of this study, it appears that rear-mounted ORVR canisters are extremely unlikely to produce an ignition following a crash. With a front-mounted enhanced recovery canister, the likelihood of ignition is significantly higher, though still low. These calculations will tend to overestimate the ignition probability, so the probabilities for ignition given here are probably high.

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