Fire Technology

DOI: 10.1007/s10694-013-0380-3

The Propensity of Lit Cigarettes to Ignite Gasoline Vapors

*Howard A. Marcus and Justin A. Geiman**, Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF), U.S. Department of Justice, 6000 Ammendale Rd., Beltsville, MD 20705, USA*

Received: 8 August 2013/**Accepted:** 7 December 2013

Abstract. Fire investigators regularly evaluate available fuels and potential ignition sources to determine the cause of a fire. This work examined the propensity of lit cigarettes to ignite gasoline vapors, expanding on previous work to include a large number of trials and a wide range of test conditions. Experiments were conducted exposing lit cigarettes, both at idle and under draw, to gasoline vapors in various configurations including pools/pans of gasoline, gasoline on textile substrates (clothing), and sprays of gasoline. Five major brands of commercially-manufactured tobacco cigarettes were tested. The experiments conducted for this study consisted of 70 distinct tests involving a total of 723 cigarettes and over 4,500 instances of exposure of a lit cigarette to ignitable concentrations of gasoline vapor in air. There were no instances of the ignition of gasoline vapors from the exposure of those vapors to a lit tobacco cigarette during any of the experiments.

Keywords: Fire investigation, Ignition, Cigarettes, Gasoline

1. Introduction

Fire cause determination involves determining how a fuel, an ignition source and an oxidizer combine to cause a fire [1]. NFPA 921 cautions investigators not to prematurely conclude the cause of a fire based solely on the presence of a readily available fuel and a potential ignition source, but rather to understand the ignition sequence and determine whether a competent ignition source exists for the first material ignited (see §18.4.2 and §18.4.4 of NFPA 921 [1]).

Lit cigarettes are a potential ignition source that may need to be considered by fire investigators at many scenes. There were an estimated 90,800 reported smoking-material fires in the US in 2010 [2]. An additional 155,000 home cigarette fires go unreported each year, according to a study by the US Consumer Product Safety Commission [3]. Despite the prevalence of smoking material fires overall, cigarettes are generally considered to be poor ignition sources for ignitable liquids. This study examines whether a lit tobacco cigarette, commercially manufactured in the US, is a competent ignition source for gasoline vapors.

Gasoline is one of the most prevalent flammable liquids [4]. It has also been referred to as the "most dangerous substance routinely handled by untrained

* Correspondence should be addressed to: Justin A. Geiman, E-mail: justin.geiman@atf.gov

Published online: 24 December 2013

individuals'' [5]. Gasoline is an engineered mixture of volatile, low boiling point, midrange hydrocarbons blended with a variety of additives that readily produces flammable vapors at ambient temperatures [6]. Recent US fire statistics show that there are an estimated 2,400 residential structure fires annually involving gasoline, with approximately half of these fires categorized as intentional [7].

The objective of this study was to expand the previous work on the propensity of lit cigarettes to ignite gasoline vapors to a wide range of test conditions in configurations of practical interest to fire investigators. Experiments were conducted exposing lit tobacco cigarettes, both at idle and under draw, to gasoline vapors in various configurations. Tested configurations included gasoline in a pan, on a horizontal surface, on a variety of textile substrates (clothing), and as a mist.

1.1. Literature Review

Cigarette ignition of ignitable liquids and gases has been studied previously in the literature [8–14]. Babrauskas [5] and Holleyhead [12] provide comprehensive reviews of the subject. The consensus in the literature is that cigarettes make poor ignition sources for most ignitable liquids and gases, but that it is possible to ignite a limited set of ignitable liquids and gases with a cigarette. The eight substances that have been ignited by lit cigarettes in laboratory experiments are shown in Table 1.

In contrast, 45 different ignitable liquids and gases have been shown not to ignite when exposed to cigarettes in laboratory experiments (see Geiman and Fuss [15] for a detailed list). Many common ignitable liquids and gases do not ignite in the presence of lit cigarettes including fuels such as butane, propane, heptane, methane; alcohols such as methanol, ethanol, isopropanol; and solvents such as acetone, methyl ethyl ketone, and xylene.

Prior to examining the previous experimental studies involving ignition of gasoline with cigarettes, it is instructive to examine the properties of both cigarettes and gasoline. Commercial cigarettes are typically 60 mm to 100 mm long, with a diameter of 7.8 mm to 8.1 mm, and a weight of 0.6 g to 1.1 g [5]. Holleyhead [12] provided a detailed explanation of the cigarette combustion process, including the

Table 1
Ignitable Liquids and Gases Ignited by Cigarettes

Fuels	References
Acetylene	[9]
Carbon disulphide	[8, 9]
Ethylene oxide	[9]
Diethyl ether	[9, 11]
Hydrogen	[9, 10]
Hydrogen sulphide	[9]
Phosphine	[9]
Toluene[a]	[8][a]

[a] One test only, no ignition in subsequent tests

temperature, velocity, and gas species concentrations (oxygen, carbon monoxide, and carbon dioxide) produced. Table 2 summarizes the gas- and solid-phase temperatures associated with lit cigarettes.

Gasoline has a flash point of −38°C to −43°C and an auto-ignition temperature (AIT) of 280°C to 456°C [16]. A range of values for flashpoint and AIT are listed because they vary depending on the grade (octane-rating) of the gasoline. Modern automotive gasoline typically has an AIT of 440°C to 450°C [5]. Based solely on the temperatures listed in Table 2 and the combustion properties of gasoline, fire investigators often assume that ignition of gasoline by a cigarette is not only possible, but likely. However, evaluating the ignition process for this scenario is more complicated than simply comparing these temperature measurements.

Research into the ignition of gasoline on a hot surface, a problem with similarities to cigarette ignition of gasoline, has shown that, in general, hot surface temperatures need to significantly exceed the AIT for ignition to occur. Hot surface ignition of ignitable liquids is probabilistic in nature, and occurs over a range of temperatures over which ignition becomes more likely [17–19]. Colwell and Reza [17] developed a logistical regression curve based on series of hot surface ignition experiments with unleaded 87 octane gasoline, which showed a 10 % probability of ignition at approximately 610°C and a 90 % probability of ignition at approximately 660°C. Davis et al. [18] reported hot surface ignition at temperatures as low as 667, 670, and 735°C, respectively for 87-, 89-, and 93-octane gasoline. They showed that the hot surface ignition temperature generally increases with increasing octane number for standard gasoline blends. Recent work by Shaw et al. [19] found minimum hot surface ignition temperatures of 530°C for gasoline using a different experimental approach.

While the hot surface ignition temperatures for gasoline may seem to support the possibility that cigarettes can ignite gasoline, it is important to remember that hot surface ignition is a complex phenomenon, dependent on numerous factors including surface properties, environmental conditions, and properties of the ignitable liquid [18]. Of particular relevance to cigarette ignition of gasoline, it has been shown that hot surface ignition temperature is dependent on the size of the hot surface [5, 20]. As the area of the hot surface decreases, the hot surface ignition temperature increases. The previously mentioned studies on the hot surface ignition of gasoline involved hot surfaces several orders of magnitude larger than the size of the hot surface of a lit cigarette. Since hot surface ignition temperatures are so strongly dependent on the test conditions, the hot surface ignition

Table 2
Temperatures Associated with Lit Cigarettes [12]

Peak temperature	Idle cigarette (°C)	Puffed cigarette (°C)
Gas phase	700–850	850
Solid phase	700–850	900–950[a]

[a] Maximum transient temperatures of 1,200°C were measured at the paper burn line in one study, at the start of a puff only

temperatures for gasoline listed above may not be relevant to cigarette ignition of gasoline, but they do suggest that the surface temperature of the cigarette would likely need to be significantly greater than the AIT to cause ignition.

Unlike hot surface ignition, cigarette ignition of gasoline has the additional complication of having conditions in the combustion region of the cigarette that are unfavorable to ignition. Holleyhead [12] reported oxygen-deficient conditions in the combustion region of the cigarette, with high concentrations of carbon dioxide, and air velocities through the cigarette of up to 400 cm/s. At the center of the cigarette coal, where temperatures are highest, oxygen is almost entirely depleted, with other areas of the coal having oxygen concentrations of less than 10 % by volume [12]. Concentrations of carbon dioxide in the cigarette coal are reported to be as high as 17.5 % by volume [12]. With velocities of up to 400 cm/s in the cigarette while being puffed, the residence time of gases or vapors in the high temperature region of the cigarette coal are typically less than 1 ms [12]. As a result, gases or vapors entering the cigarette coal when the temperatures are at a maximum (during puffing), have a limited exposure period during which to heat to their ignition temperature. All these conditions create an environment unfavorable to ignition, and result in an ignition process that is more complex than a simple temperature comparison.

There is not a clear consensus on the factors that explain the ignition, or lack of ignition, for substances by cigarettes in laboratory experiments. Various factors have been proposed, including flammability limits, surface temperature, residence time and ignition delay, burning velocity, minimum ignition energy (MIE), quenching distance, and insulating effect of the ash [1]. No single combustion parameter explains the ignition, or lack thereof, for ignitable liquids or gases by cigarettes [12]. However, in general, substances that have been ignited via a cigarette have smaller quenching distances, wider flammable ranges, lower MIE, and slightly lower AITs than substances that do not ignite [12]. Table 3 compares gasoline to substances that have been ignited by a cigarette.

Table 3
Comparison of Gasoline to Substances that Have Been Ignited by Cigarettes [5, 20]

Fuels	Quenching distance (mm)	Flammable range (%)	MIE (mJ)	AIT (°C)	Ignited by cigarettes
Gasoline	2–3[a]	1–7	0.8	440	No
Acetylene	0.65	2.5–100	0.03	305	Yes
Carbon disulphide	0.55	1.2–50	0.039	90	Yes
Ethylene oxide	1.18	3.6–100	0.105	429	Yes
Diethyl ether	1.85	1.9–36	0.79	195	Yes
Hydrogen	0.64	4.0–75	0.03	400	Yes
Hydrogen sulphide	–	4.0–44	0.077	260	Yes
Phosphine	–	1–100	–	100	Yes

[a] Value estimated from correlation of MIE and quenching distance [21]

The Propensity of Lit Cigarettes

Despite the lack of a theory in the literature as to why cigarettes ignite some substances, and not others, the general trends in Table 3 are consistent with the hypothesis that gasoline is unlikely to be ignited by a cigarette. The quenching distance may be relevant to cigarette ignition in that it is possible that the tobacco fibers of the cigarette may act similar to a flame arrestor, and prevent any ignition that occurs within the cigarette to propagate to fuel vapors outside the cigarette [12]. This effect has not been shown experimentally, so it is unclear whether the larger quenching distance of gasoline is indeed significant.

The flammable range for gasoline is narrower, with a significantly lower upper flammable limit (UFL), than the substances that have been ignited by cigarettes. The narrow flammable range means that the volume of the fuel–air mixture over which ignition may occur is significantly less than the substances ignited by cigarettes. MIE is a metric for the amount of energy transfer required for ignition to occur. Stresse [9] observed that fuels with an MIE of less than about 0.08 mJ were ignited by cigarettes, while those with higher MIE values generally did not ignite. The MIE of gasoline is an order of magnitude greater than the value suggested by Stresse, indicating that it is unlikely to ignite. However, diethyl ether has an MIE similar to gasoline and it is ignited by cigarettes. Similarly, the AIT of gasoline was higher than most substances ignited by cigarettes. However, hydrogen and ethylene oxide were ignited by cigarettes despite AITs similar to gasoline. When taken as a whole, the data in Table 3 indicate substances ignited by cigarettes are, in general, more reactive and more easily ignited than gasoline. However, there are some inconsistencies in the data, and therefore experimental investigation is necessary to fully address the issue.

Existing experimental evidence supports the hypothesis that cigarettes will not readily ignite gasoline. The *Ignition Handbook* [5] notes that several papers report that gasoline vapors are not ignited in cigarette experiments [8, 10, 12]. DeHaan [6] noted anecdotally that throwing or dropping lit cigarettes into the vapors above a gasoline pool had never resulted in ignition, however no details on the experiments were provided.

Yockers and Segal [8] conducted a series of experiments involving various flammable liquids and gases. In the experiments, they saturated a 7.6 cm (3 in.) square of asbestos cloth with the liquid and exposed it to three different cigarette conditions—a lit cigarette, a lit cigarette under draw, and glowing coals from a cigarette. Each liquid was tested three times, and none of the experiments with gasoline resulted in ignition.

Schuh and Sanderson [13] found that no ignitions occurred in 100 attempts to ignite gasoline with a lit cigarette, in various configurations. Specifically, none of the 20 cigarettes they dropped into liquid gasoline caused ignition. Likewise, no ignitions occurred when cigarettes under draw were placed above the surface of the liquid [up to 0.3 m (1 ft) away]. Even when gasoline was misted on lit cigarettes no ignitions occurred.

A recent study by Jewell et al. [14] examined lit commercial cigarettes, hand-rolled cigarettes, and cannabis resin joints exposed to gasoline vapors. A total of 30 ignition attempts were conducted by placing lit cigarettes/joints 20 cm to 50 cm (8 in. to 20 in.) above a pool of liquid gasoline in a pan. An additional nine ignition attempts involved a mannequin dressed in cotton clothing that was splashed with various amount of gasoline ranging from 20 mL to 500 mL and exposed to lit cigarettes/joints under draw from a pump. No ignition of gasoline vapors was observed in the 39 ignition attempts.

The primary criticisms, or caveats, related to the previous experimental work on the ignition of gasoline by a lit cigarette were the limited number of experiments and limited range of conditions under which tests were conducted [5]. It has even been suggested that an "infinite number of experiments" would be required to completely disprove cigarettes as a possible ignition source for ignitable liquids and gases [5, 11]. While this may be true, in a strict scientific sense, the existing data has shown that the ignition of gasoline vapors by a cigarette is an unlikely event requiring a unique set of circumstances that has yet to be identified. From a practical standpoint for fire investigators, a cigarette has not been shown to be a competent ignition source for gasoline vapors in laboratory testing. The present study was designed to address the limitations of the previous experimental work by conducting a large number of cigarette exposures to gasoline and considering a wide range of conditions to explore the possibility of the ignition of gasoline by a cigarette in as empirically-sound manner as possible.

1.2. Case Studies

Whether cigarettes are a competent ignition source for gasoline vapors is more than just an academic argument, the scenario is encountered by fire investigators on a regular basis. A common scenario where the ignition of gasoline vapors by a cigarette is in question involves two people, often a man and a woman, where one or both are smokers. The scenario often unfolds where the victim accidentally came in contact with liquid gasoline, according to the witness, and the gasoline vapors were subsequently ignited by a cigarette. The witness, who was in close proximity to the victim, sustained no injuries or only minor injuries. Several case studies are presented in this section to illustrate the prevalence of this scenario.

On 23 June 2002 a Grand Rapids, Michigan woman was severely burned, and later died, after gasoline on her body was ignited while she was sitting in the passenger seat of a Ford Bronco. Her boyfriend, who was in the driver's seat, sustained burns to the inside of his arms and hands, and flash burns to his face.

Initially he reported that an unsealed five gallon plastic gasoline container containing one gallon of gasoline was located on the floor of the vehicle between the victim's feet. His account of the event was that the victim was smoking a cigarette and she suddenly ignited due to gasoline spilled on her hands from filling the container. Later, he changed his story and reported that they were arguing and she poured gasoline on herself and committed suicide. Evidence showed that the victim and her boyfriend were arguing violently prior to the incident with the gasoline container on the center console prior to the fire and that the boyfriend poured gasoline on the victim and ignited it with a lighter. The boyfriend was convicted of second degree murder after a jury trial in Kent County (Michigan) Circuit Court and was sentenced to life in prison.

On 28 March 2003, a South Holland, Illinois woman was burned after gasoline was spilled or poured on her torso and ignited. A friend claimed that his burning cigarette accidentally ignited the spilled gasoline, which caused serious burns to her head, face, arms, neck, upper back and upper chest. He received treatment for burns on his right hand. The man was later convicted of heinous battery, a Class X felony in Illinois, and was sentenced to 12 years in prison.

On 4 October 2004, two police officers were burned in Harlingen, Texas as they responded to a domestic dispute. The officers followed a man carrying a gasoline container into his residence. The man claimed he dropped the gasoline container, splashing gasoline onto one of the officers, and dropped a cigarette accidentally, which ignited the gasoline. The first officer received third degree burns over 75 % of his body and the second officer, a few feet behind him, received flash burn injuries. Evidence showed that the man had poured a trail of gasoline behind him while running through the house. He then ignited the opening of the gasoline container with his lighter and threw the container at the officers. The man was found guilty of two counts of aggravated assault on a peace officer and one count of arson of a residence, and was sentenced to consecutive sentences of 50 and 25 years, respectively.

2. Experimental Setup

Experiments were conducted exposing lit, commercially-manufactured tobacco cigarettes, both at idle and under draw, to gasoline vapors in various configurations. Testing configurations included gasoline in a pan, on a horizontal surface, on a variety of textile substrates (clothing), and as a spray. These configurations were selected so as to consider realistic scenarios that provided favorable conditions for the ignition of the gasoline vapors.

All experiments used regular 87 octane automotive gasoline purchased at a commercial gasoline station in January 2005. The exact composition of the gasoline was not determined, however it is likely that the gasoline contained up to 10 % ethanol. Prior to each test, the desired amount of liquid gasoline was poured from a portable fuel storage container into a graduated cylinder. The gasoline was then splashed, poured, or sprayed during the test according to the specific test configuration. Some tests involved multiple cigarettes per test, with multiple probes of the gasoline vapors per cigarette. At the conclusion of each test, an open flame ignited the gasoline vapors. This process verified that the cigarettes were exposed to a gasoline vapor–air mixture that was within the flammability limits during the experiment.

2.1. Cigarette Exposures

The cigarettes utilized in these experiments were commercially manufactured tobacco cigarettes purchased from retail outlets. The cigarette brands selected for this study were Marlboro (M), Marlboro Light (ML), Newport (N), Camel (C), and C without filter (CNF). M, N, and C represent the three most popular cigarette brands purchased by consumers in the US, representing approximately 56 %

of overall sales [22]. The physical parameters and burning behavior of commercial tobacco cigarettes, including their competence as an ignition source, were consistent across cigarette brands [5, 23].

None of the cigarettes used in this study were Fire Standards Compliant (FSC) cigarettes. FSC cigarettes, often referred to as ‘‘fire safe cigarettes’’, are designed to self-extinguish more quickly than standard cigarettes. At the time these tests were conducted (2005), FSC cigarettes were not prevalent. Any differences in ignition performance between current FSC cigarettes and the non-FSC cigarettes used in this study are expected to be negligible with regards to the ignition of gasoline.

Cigarettes were tested under two basic conditions—idle and under draw. An idling cigarette refers to a lit and glowing cigarette not actively being smoked. Holleyhead [12] referred to this condition as natural smoldering, the burning that occurs between draws or puffs of a cigarette by a smoker. A cigarette tested under draw refers to a suction or draw being applied to the unlit end of a cigarette to provide a severe exposure at the lit end of the cigarette. This condition is also referred to as induced smoldering or puffing of the cigarette.

For experiments conducted with cigarettes under draw, a vacuum draw apparatus was constructed to produce a steady draw condition on the lit cigarette to provide a severe exposure at the lit end of the cigarette [24]. Guidance on the design and operation of this apparatus was based on a mock-up ignition test method procedure developed by the National Institute of Standards and Technology for cigarette ignition of upholstered furniture [24]. Figure 1 shows the vacuum draw apparatus. The test apparatus consisted of a vacuum pump connected via flexible tubing to a flowmeter with a needle valve, which was connected via flexible tubing to a cigarette holder. The holder contained a flexible diaphragm with a hole sized to seal around the filter end of the cigarette and a fibrous particulate filter. This apparatus provided a means to pull air through the lit cigarette at a rate of 1 L/min $\pm$ 200 mL/min. The holder was attached to a 0.9 m (3 ft) rod so that a lit cigarette, under draw, could be used to probe the gasoline vapors from a safe distance.

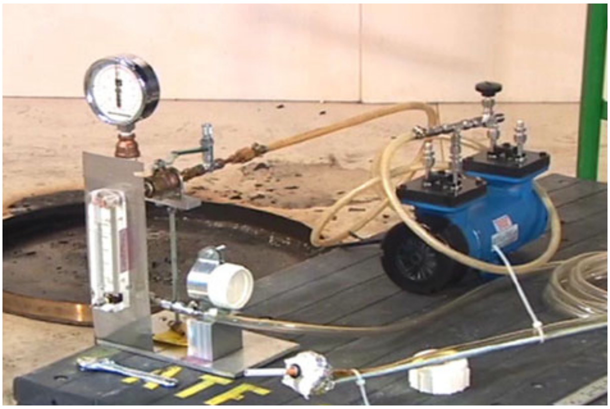

Figure 1. Cigarette vacuum draw apparatus.

Several methods were employed to bring the cigarettes and gasoline into contact—gasoline introduced near lit cigarettes, tossing cigarettes into gasoline liquid/vapors, and probing gasoline liquid/vapors with a cigarette. The first method involved gasoline poured, splashed, or sprayed in the presence of a lit cigarette, with no movement of the cigarette. Cigarettes were also tossed into liquid gasoline and gasoline vapors to consider movement of the cigarette through the vapor space.

For cigarette exposures involving pans of gasoline and gasoline on textiles, *probes* with the cigarette were used. A *probe* refers to moving the cigarette into, through, and possibly out of the gasoline vapor space. Probing was accomplished with the cigarette placed in the holder of the vacuum draw apparatus. Probing at idle was accomplished with the vacuum pump off and no forced draw through the cigarette. Probing was conducted at various locations in the area of the gasoline exposure. For the pan experiments, probing was performed at multiple locations within the pan. For the experiments with gasoline on clothing, probing was performed at various locations on and around the spill/soak location. For example, probes were conducted in the center of the spill, at the spill edges, and above and below the spill location. The exact probing locations varied for each test, and multiple probes at the same location were typically conducted during a test.

Another cigarette condition that was explored for a limited number of experiments was a shower of burning tobacco fragments produced when a lit cigarette strikes a solid surface. Babrauskas [5] suggested that this scenario provided favorable conditions for ignition. To create a shower of burning tobacco fragments, a lit cigarette was tossed against a vertical surface, as shown in Fig. 2. Note the black marks on the vertical surface, just above the burning tobacco fragments in Fig. 2. These marks are a result of the cigarettes striking the surface. The vertical surface was located such that the cigarette and resulting shower of burning tobacco fragments fell through gasoline vapors into a pan.

Figure 2. Burning tobacco fragments created by striking a solid surface.

2.2. Gasoline Configurations

Three gasoline configurations were considered in this study—pools/pans of gasoline, gasoline on textile substrates (clothing), and sprayed gasoline. Tests conducted with pools/pans of gasoline were intended to simulate spills of gasoline onto solid surfaces, or open containers of liquid gasoline. Table 4 summarizes the five pool/pan fire scenarios tested.

A 0.6 m (2 ft) diameter steel pan, 4 cm (1.5 in.) deep, containing 500 mL (17 oz) of gasoline was used for the majority of the pan experiments. In one experiment, the pan was turned upside down and only 150 mL (5 oz) of gasoline was placed on the backside of the pan. This allowed the cigarettes to be placed adjacent to the liquid gasoline without the influence of the lip of the pan.

Tests were conducted with the gasoline poured in the pan prior to, and after, the burning cigarettes were in place. In some tests, screens were placed into the pan to allow the cigarettes to burn in the vapor space above the liquid surface, without making contact with the liquid. Due to the vapor density of gasoline, the vapor space above a pool of gasoline could be fuel rich, or even above the UFL just above the liquid surface in a quiescent atmosphere [25]. The concentration of gasoline vapors will decrease with increasing height above the surface of the liquid gasoline due to diffusion and normal air circulation. To account for the potential of variable concentrations of gasoline vapors at different heights, screens were used to offset cigarettes at different heights in the gasoline vapor space. Four screens, each at a different height, were located within the pan. The height of each screen above the bottom of the pan was not recorded. Figure 3 shows the height and arrangement of the screens.

Although a wire mesh screen is often used as a flame arrestor to prevent fire spread through the screen, the screens used in the pan experiments did not prevent ignition. Since the fuel (gasoline vapors), oxygen (from the ambient air), and ignition source (cigarette or open flame) were all present on the same side of the screen, ignition still occurred. This was verified when an open flame was

Table 4
Summary of Pool/Pan Fire Scenarios

Scenarios	Gasoline quantity (mL)	Description
P1	500	Cigarettes inserted into the vapor space above a pan of gasoline
P2	500	Cigarettes placed on a screen above a pan of gasoline. Gasoline was poured into pan past cigarettes
P3	500	Cigarettes placed on screens at four different heights within the vapor space above a pan of gasoline. Gasoline was poured into pan past cigarettes
P4	150	Gasoline poured on the back of a pan. Cigarettes placed in/around gasoline on pan
P5	500	Cigarettes and glowing tobacco fragments fall into a pan of gasoline

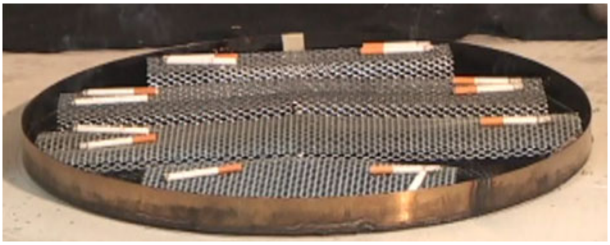

Figure 3. Screens were used to offset cigarettes at different heights above the pan.

introduced above the screen, at the same location as the cigarettes, and consistently resulted in sustained ignition of the gasoline vapors in the pan.

This procedure of introducing an open flame ignition source at the conclusion of each test was performed for each pan experiment in order to demonstrate that a flammable concentration of gasoline vapors existed in or above the pan in the area of cigarette exposure. After ignition, the fire was then extinguished, the pan was cleared of any cigarettes, and the pan was rinsed with water prior to the next test.

In tests involving gasoline on clothing, gasoline was either soaked or splashed onto a portion of the garments. The area of the garment to which gasoline was applied varied in each test based on the quantity of gasoline used, method of applying the gasoline, and the clothing material. In general, liquid gasoline was present only on a limited portion of the garment. Figure 4 shows the two methods used to apply the gasoline to the clothing. Soaking was accomplished by slowly pouring 150 mL (5 oz) of gasoline onto the garment to absorb the maximum amount of fuel into the material. Conversely, splashing the gasoline onto the clothing refers to the application of the entire volume of gasoline to the clothing surface in one abrupt motion. A smaller quantity of gasoline, 50 mL (1.7 oz), was used when the gasoline was splashed onto the clothing. In both cases, a pan was

(a) Splashing **(b)** Pouring

Figure 4. Gasoline was applied to the clothing via (a) splashing and (b) pouring.

located below the target garment to collect any liquid gasoline falling from the material. Table 5 summarizes the fire scenarios tested involving gasoline on clothing.

By using varied textile materials, a variety of absorption and wicking scenarios were considered. The use of garments in particular, rather than fabric swatches, was selected so that the tests were similar to fire scene situations that investigators encounter. Secondly, much of the previously conducted research into the ignition propensity of gasoline vapors by a cigarette involved the pool/pan of gasoline scenario. By using a textile substrate in the vertical orientation, the gasoline vapors fall from the garment due to the vapor density of gasoline. This potentially results in the mixture of the gasoline vapors and the ambient air in concentrations that may be different than those achieved in the more tightly packed vapor column present above a pool of gasoline.

The clothing utilized in these experiments was obtained both new and used from retail outlets and resale shops. Clothing description data was obtained from the labels attached to the garments; garments lacking labels were not used. Table 6 summarizes the clothing used in the experiments. Figure 5 contains photographs of selected clothing items used in the experiments.

Two methods were used to support the clothing. In some tests, mannequins were dressed with the clothing tested. Other tests were conducted with the garment supported on a wire clothing hanger.

At the conclusion of each test involving gasoline on clothing, an open flame ignited the remaining gasoline to demonstrate the presence of a flammable concentration of gasoline vapors.

Table 5
Summary of Gasoline on Clothing Fire Scenarios

Scenarios	Description	Gasoline	Cigarette exposure		Wind
T1	Cigarette probed clothing soaked with gasoline	Soak	Idle	Probe	No
T2	Cigarette under draw probed clothing soaked with gasoline	Soak	Draw	Probe	No
T3	Cigarette under draw probed clothing splashed with gasoline	Splash	Draw	Probe	No
T4	Gasoline splashed on clothing while mannequin is holding a cigarette	Splash	Idle	Holding	No
T5	Gasoline splashed on clothing while mannequin is holding a cigarette and clothing probed with a cigarette	Splash	Idle	Both	Yes
T6	Gasoline splashed on clothing while mannequin is holding a cigarette and clothing probed with a cigarette under draw	Splash	Both	Both	Yes
T7	Gasoline soaked on clothing while mannequin is holding a cigarette and clothing probed with a cigarette under draw	Soak	Both	Both	Yes

Table 6
Clothing Summary

IDs	Materials	Description	Colors
S1	100 % Cotton	T-shirt	White
S2	100 % Polyester "Dri Wick" fabric	T-shirt	Orange
B1	100 % Polyester	Blouse	Black with flowers
B2	100 % Polyester	Blouse	Blue/purple
B3	100 % Polyester velvet	Blouse	Maroon
B4	100 % Rayon	Blouse	Multi-colored
B5	55 % Ramie/45 % cotton	Blouse	Multi-colored
J1	100 % Cotton	Jeans	Blue
SS1	80 % Cotton/20 % polyester	Sweatshirt	Blue
SW1	65 % Polyester/35 % cotton	Sweater	Red
SW2	55 % Ramie/45 % cotton	Sweater	Multi-colored
D1	100 % Silk	Dress	Red
C1	100 % Nylon	Coat	Black
C2	Exterior: 100 % leather Liner: 50 % nylon/50 % acetate	Coat	Black
C3	Exterior: 52 % polyester/48 % acetate Liner: 100 % acetate	Coat	Black
C4	Exterior: 100 % wool Liner: 100 % nylon sateen	Coat	Gray

The final gasoline configuration considered in this study was a spray of gasoline. Spray from a failed hose, mist liberated by a malfunctioning pump, or splatter from dropped or spilled gasoline could account for the presence of a spray, mist, or fine droplets of the fuel in the presence of a cigarette. Liquids, in the form of a spray, are known to ignite readily, even at temperatures below their flashpoint [20, 26]. In addition, Babrauskas [5] notes that the MIE of gasoline decreases from 5 mJ at its flashpoint to 0.6 mJ at 10°C when in the form of a spray. Given the ease of ignition and low energy levels required to ignite a spray of gasoline at ambient temperatures, exposing a lit cigarette to a spray of gasoline would seem to be a scenario highly favorable to ignition.

For this study, cigarettes were introduced to a spray of gasoline while in the draw apparatus previously described. Tests were also conducted where an open flame was introduced into the spray of gasoline. The spray was produced with a newly purchased small spray bottle, similar to those used to spray cologne. The spray bottle was mounted on an apparatus that could actuate the pumping mechanism of the sprayer multiple times from a safe distance. Figure 6 shows the gasoline sprayer apparatus used in this study. The size distribution of the spray produced by this apparatus was not quantified.

2.3. Environmental Conditions

Environmental conditions in the laboratory during the testing were monitored and recorded. Ambient temperatures and gasoline temperature were measured using Type K thermocouples. Ambient air temperatures monitored in the laboratory during testing ranged from 12°C to 19°C (54°F to 66.0°F). The temperature of the

Figure 5. Selected clothing used in the experiments.

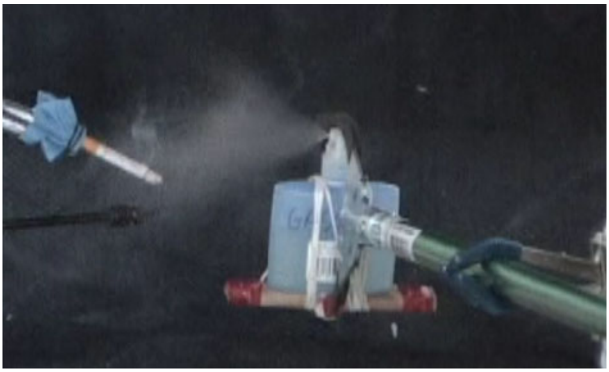

Figure 6. Gasoline sprayer apparatus.

gasoline used in testing ranged from 8°C to 17°C (47°F to 63°F). Tests were conducted in both a quiescent environment, and with wind provided by an electric fan. Wind speeds of up to 1 m/s (2.2 miles/h) and 2 m/s (4.5 miles/h) were used during testing. Wind speed was measured using a Kestrel Pocket Thermo Wind Meter approximately 15 cm (6 in.) above the upwind lip of the pan containing gasoline or at the target in tests involving garments. The relative humidity of the ambient air during testing ranged from 29 % to 82 %. Barometric pressure during the testing was nominally one atmosphere.

3. Results and Discussion

A total of 70 experiments were conducted over a period of 7 days from 6 January 2005 to 14 January 2005. Of the 70 experiments conducted, 64 involved exposing lit cigarettes to gasoline. Each experiment typically involved multiple exposures of cigarettes to gasoline. A total of 723 cigarettes were used during the test series. The remaining six tests (Tests 1.0, 1.1, 1.2, 9.5, 9.7, and 20.0) did not include cigarettes; gasoline was ignited with an open flame in these tests. The identifiers for the experiments are not numbered sequentially; they were retained from an unpublished report by one of the authors which has been admitted to court on multiple occasions.

Thirty experiments were conducted with lit cigarettes exposed to pools or pans of gasoline. In these 30 experiments, 591 cigarettes were exposed to gasoline vapors, often multiple times, in various conditions. Tables 7, 8, and 9 detail the experiment conditions and results of the cigarette exposures to pans of gasoline. In these tables, the brands of cigarette used in the experiments are referred to using the following nomenclature: M, ML, N, C, and CNF. The naming convention for the pan scenarios is given in Table 4.

Table 10 and Fig. 7 summarize the overall results from these experiments. No ignition of gasoline vapors was observed in any of the 734 ignition attempts in this configuration.

Table 7
Summary of Pan Experiments for Scenario P1

			Number of ignitions/number of attempts		
Test	Cigarette brand	Wind speed (m/s)	Probe (idle)	Probe (draw)	Open flame
1.0					1/1
1.1					1/1
1.2					1/1
2.0	M		0/1		0/0
2.1	M		0/7		0/0
2.2	M		0/7		1/1
2.3	M		0/16		1/1
3.0	M			0/5	0/0
3.1	M			0/3	1/1
4.0	M	1.1	0/15		1/1
4.1	M	2.0	0/12		1/1
5.0	M	1.1		0/9	1/1
5.1	M	2.0		0/15	1/1
Total			0/58	0/32	

Table 8
Summary of Pan Experiments for Scenarios P2, P4, and P5

			Number of ignitions/number of attempts		
Test	Scenarios	Cigarette brands	Idling	Thrown	Open flame
17.0	P4	M, ML, N, C	0/51	0/31	1/1
18.0	P2	M, C, N, ML, CNF	0/50		1/1
18.1	P2	M, C, N, ML, CNF	0/48		1/1
19.0	P2 and P5	M, ML, N, C	0/24	0/55	1/1
19.1	P2 and P5	M, ML, N, C	0/24	0/56	1/1
19.2	P2 and P5	M, ML, N, C	0/24	0/28	1/1
Total			0/221	0/170	

Table 9
Pan Experiments for Scenario P3

			Number of ignitions/number of attempts		
Test	Scenarios	Cigarette brands	Idling	Probe (draw)	Open flame
22.0	P3	M, ML, N, C	0/16		1/1
22.1	P3	M, ML, N, C	0/16		1/1
22.2	P3	M, ML, N, C	0/16		1/1
23.0	P3	M, N, C, ML	0/16		1/1
23.1	P3	M, N, C, ML	0/16		1/1
23.2	P3	M, N, C, ML	0/16		1/1
23.3	P3	M, N, C, ML	0/16		1/1
23.4	P3	M, N, C, ML, CNF	0/16	0/17	1/1
23.5	P3	M, N, C, ML, CNF	0/16	0/52	1/1
23.6	P3	M, N, C, ML, CNF	0/20		1/1
23.7	P3	M, N, C, ML, CNF	0/20		1/1
Total			0/184	0/69	

Table 10
Summary of Pan Experiments

Description	Number of ignitions/number of attempts
Idling cigarettes	0/405
Thrown cigarettes	0/170
Probes with idle cigarette	0/58
Probes with cigarette under draw	0/101
Total	0/734

Thirty-seven experiments were conducted with lit cigarettes exposed to gasoline on textile substrates (clothing). In these 37 experiments, 129 cigarettes were exposed to gasoline vapors, often multiple times, in various conditions. Tables 11

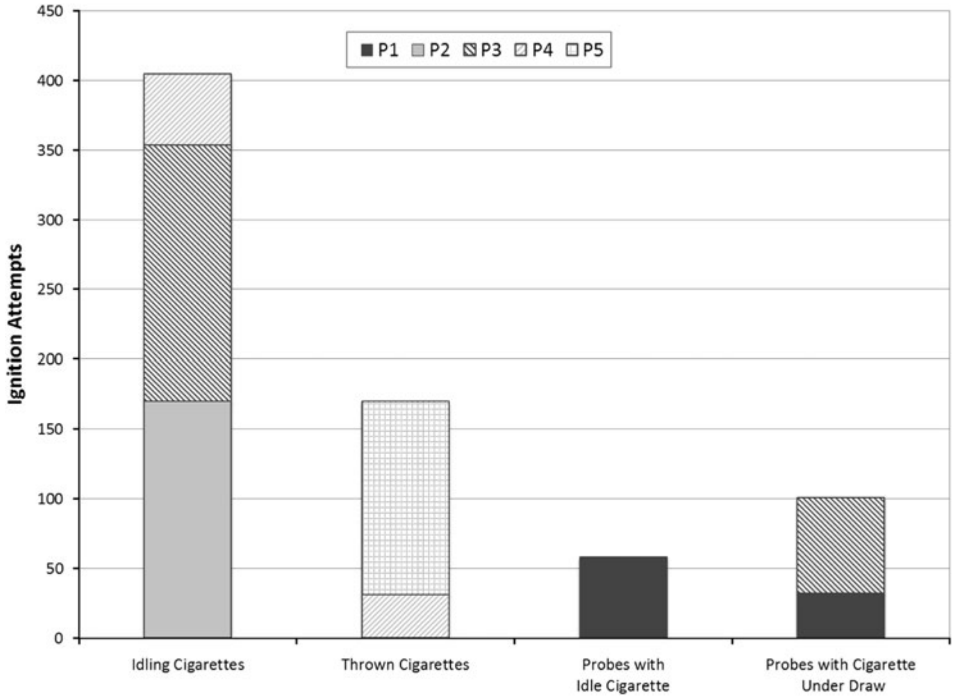

Figure 7. Summary of pan fire experiments by scenario.

and 12 detail the experiment conditions and results of the cigarette exposures to gasoline on clothing. The same abbreviations are used for the cigarette brands as in the previous tables. The scenario and clothing identifiers listed in Tables 11 and 12 refer to those listed in Tables 5 and 6, respectively.

Table 13 and Fig. 8 summarize the overall results from the clothing experiments. No ignition of gasoline vapors was observed in any of the 3,533 ignition attempts in the clothing experiments.

Three experiments were conducted with sprays of gasoline. Table 14 details the results of the spray experiments. The same abbreviations are used for the cigarette brands as in the previous tables. When the gasoline spray was applied to an open flame, the gasoline ignited and a fireball immediately ensued. No ignitions caused by cigarettes occurred during these experiments.

One observation noted in both the pan experiments and spray experiments was the ability of the liquid gasoline to extinguish combustion in the cigarette. This phenomenon was observed in ten of the pan experiments. For example, when a lit cigarette was dropped into a pan of liquid gasoline, white vapors were visible when the cigarette first entered the liquid. Once in contact with the liquid gasoline, the cigarette absorbed the gasoline and wicked gasoline through the remainder of the cigarette, ceasing combustion. A similar process was observed with sprays of gasoline following multiple sprays on the same cigarette.

Table 11
Clothing Experiments for Scenarios T1–3

				Number of ignitions/number of attempts		
Test	Scenarios	Clothing IDs	Cigarette brands	Probe (idle)	Probe (draw)	Open flame
6.0	T1	S1	M, N, C	0/215		1/1
6.1	T1	B4	CNF	0/164		1/1
7.0	T2	S1	M, N, C, ML		0/108	1/1
7.1	T2	B1	ML, N, C, M		0/314	1/1
7.2	T2	J1	N, ML, M, C		0/484	1/1
7.3	T2	B4	CNF		0/45	1/1
7.4	T2	B5	CNF		0/29	1/1
7.5	T2	B2	N		0/32	1/1
7.6	T2	SS1	ML		0/38	1/1
7.7	T2	SW2	M		0/39	1/1
7.8	T2	S2	C		0/20	1/1
9.0	T3	SW1	C, M, ML, N		0/863	1/1
9.1	T3	B3	ML, M, C, N		0/922	1/1
9.2	T3	C1	N		0/33	1/1
9.3	T3	C1	C		0/40	1/1
9.4	T3	C2	ML		0/9	1/1
9.5	T3	C2				1/1
9.6	T3	C2	C		0/12	0/1
9.7	T3	C2				1/1
Total				0/379	0/2,988	

Table 15 summarizes all the cigarette ignition attempts of gasoline conducted in this study. In total, over 4,500 attempts to ignite gasoline were conducted. No ignition of gasoline by a cigarette was observed in any configuration tested.

In contrast, an open flame introduced into the same gasoline configurations to which the cigarettes were tested ignited the gasoline vapors in 87 of the 88 ignition attempts. This confirmed that the cigarettes were exposed to flammable concentrations of gasoline vapor, and indicated that the cigarettes were not competent ignition sources.

The results of these tests are limited to commercially-manufactured tobacco cigarettes. This study did not address hand-rolled cigarettes, cigars, marijuana cigarettes, or other tobacco products. See Babrauskas [5] and Jewell et al. [14] for discussion of these topics.

One question that often arises as part of a study on ignition propensity of cigarettes is whether the results show that it is ‘‘impossible’’ to ignite gasoline with cigarettes. Some researchers have even gone as far as saying that an ‘‘infinite number of experiments’’ would be required to completely disprove cigarettes as a possible ignition source [5, 11]. The scientific method dictates that hypotheses should be testable and falsifiable, meaning that a test of the hypothesis can be conducted that would disprove the hypothesis. In addition, Popper [27] introduced the concept of *degree of corroboration* of a hypothesis, meaning that ‘‘it is not so much

Table 12
Clothing Experiments for Scenarios T4–7

					Number of ignitions/number of attempts			
Test	Scenarios	Clothing IDs	Cigarette brands	Wind speed (m/s)	Idling	Probe (idle)	Probe (draw)	Open flame
10.0	T4	C3	C		0/3			1/1
11.0	T5	C3	N	1.0	0/1	0/5		1/1
11.1	T5	C3	ML	1.0	0/1	0/5		1/1
11.2	T5	C3	C	2.0	0/1	0/5		1/1
11.3	T5	C3	M	2.0	0/1	0/5		1/1
13.0	T6	C3	M	1.0	0/1		0/5	1/1
13.1	T6	C3	CNF	1.0	0/1		0/5	1/1
13.2	T6	C3	N	2.0	0/1		0/9	1/1
13.3	T6	C3	ML	2.0	0/1		0/5	1/1
13.4	T6	C4	C		0/3		0/6	1/1
13.5	T6	C4	M		0/3		0/5	1/1
13.6	T6	C4	CNF	1.0	0/3		0/7	1/1
15.0	T7	C4	N	1.0	0/3		0/8	1/1
15.1	T7	C4	C	1.0	0/3		0/6	1/1
15.2	T7	C4	ML	2.0	0/3		0/5	1/1
15.3	T7	C4	M		0/3		0/10	1/1
15.4	T7	D1	M		0/3		0/20	1/1
15.5	T7	D1	N		0/3		0/17	1/1
Total					0/38	0/20	0/108	

Table 13
Summary of Clothing Experiments

Description	Number of ignitions/number of attempts
Idling cigarettes	0/38
Probes with idle cigarette	0/399
Probes with cigarette under draw	0/3,096
Total	0/3,533

the number of corroborating instances… as the severity of the various tests to which the hypothesis in question can be, and has been, subjected".

The hypothesis that lit cigarettes do not ignite gasoline is highly testable, falsifiable, and has a high degree of corroboration. As the number of studies examining this hypothesis [6, 8, 10, 12–14] indicates, it is trivial to construct a test that would falsify the hypothesis. A single ignition of gasoline by a lit cigarette would invalidate the hypothesis, and given the availability of both gasoline and cigarettes, designing such a test of the hypothesis is straightforward. One of the goals of the present study was to address the degree of corroboration of this hypothesis by exposing it to severe tests including cigarettes under draw, which offer a severe cigarette exposure, and gasoline in various configurations including sprays of

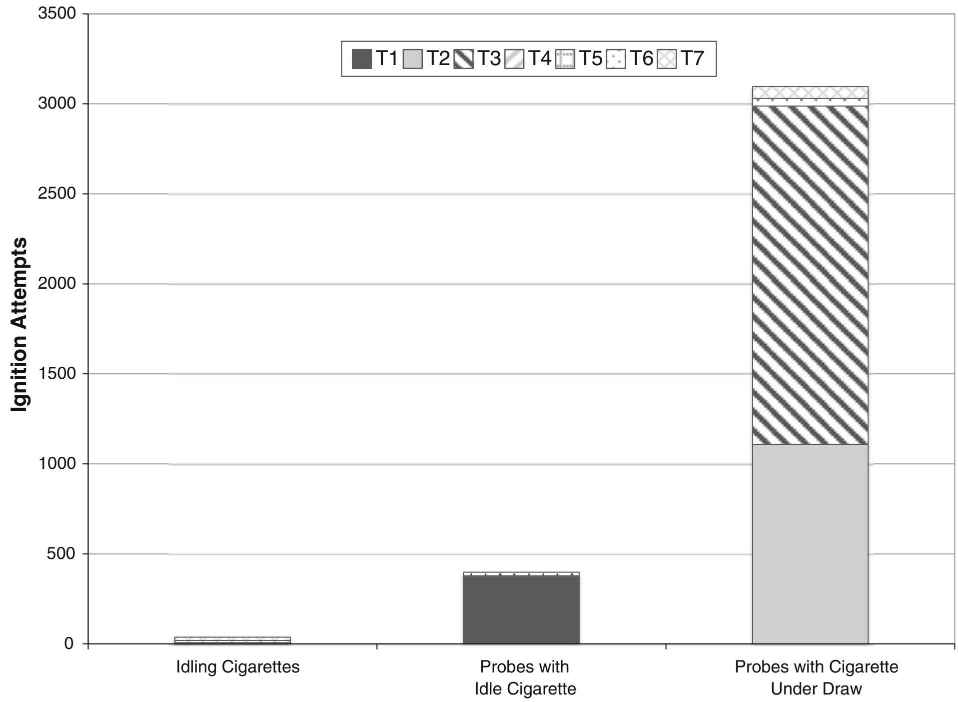

Figure 8. Summary of clothing fire experiments by scenario.

Table 14
Spray Experiments

		Number of ignitions/number of attempts		
Test	Cigarette brand	Idling	Probe (draw)	Open flame
20.0				16/16
21.0	M	0/106		3/3
21.1	M		0/145	5/5
Total		0/106	0/145	

Table 15
Summary of Cigarettes Ignition Attempts

	Number of ignitions/number of attempts			
Description	Pans	Clothing	Sprays	Total
Idling cigarettes	0/405	0/38	0/106	0/549
Thrown cigarettes	0/170			0/170
Probes with idle cigarette	0/58	0/399		0/457
Probes with cigarette under draw	0/101	0/3,096	0/145	0/3,342
Total	0/734	0/3,533	0/251	0/4,518

gasoline, which present the fuel in a form highly favorable to ignition. Popper [27] notes that a well corroborated hypothesis is one which ‘‘has been severely tested… [and] has stood up well to the severest tests we were able to design so far’’. The hypothesis that lit cigarettes do not ignite gasoline has withstood a significant number of challenges, by various investigators, under a variety of severe tests. In this way, the hypothesis is well corroborated.

From a practical standpoint, fire investigators want to know whether cigarettes are a competent ignition source for gasoline. Based on the currently available experimental data, derived under controlled laboratory conditions from this and other studies, there is no evidence that a cigarette is a competent ignition source for gasoline vapors.

4. Conclusions

Fire investigators regularly evaluate available fuels and potential ignition sources to determine the cause of a fire. This work examined the propensity of lit cigarettes to ignite gasoline vapors, expanding on previous work to include a large number of trials and a wide range of test conditions. Experiments were conducted exposing lit cigarettes, both at idle and under draw, to gasoline vapors in various configurations including pools/pans of gasoline, gasoline on textile substrates (clothing), and sprays of gasoline.

The experiments conducted for this study consisted of 70 distinct tests involving a total of 723 cigarettes and over 4,500 instances of exposure of a lit cigarette to ignitable concentrations of gasoline vapors in air. There were no instances of the ignition of gasoline vapors from the exposure of those vapors to a lit, major brand, tobacco cigarette, commercially manufactured in the US, during any of the experiments. In contrast, an open flame ignition source exposed to the same gasoline configurations resulted in ignition in all but one attempt.

While it is impossible to conduct an infinite number of experiments to provide absolute proof that ignition of gasoline could never happen with a lit cigarette, based on the currently available experimental data, derived under controlled laboratory conditions from this and other studies, there is no evidence that a cigarette is a competent ignition source for gasoline vapors.

References

1. NFPA 921 (2011) Guide for fire and explosion investigations, 2011rd edn. National Fire Protection Association (NFPA), Quincy
2. Hall JR Jr (2012) The smoking-material fire problem. National Fire Protection Association (NFPA), Quincy
3. Greene MA, Andres C (2009) 2004–2005 National sample survey of unreported residential fires. Table 6-6. U.S. Consumer Product Safety Commission
4. Slye OM Jr (2008) Flammable and combustible liquids. In: Fire protection handbook, 20th edn, Section 6, Chapter 12. National Fire Protection Association (NFPA), Quincy, pp 6–198
5. Babrauskas V (2003) Ignition handbook. Fire Science Publishers, Issaquah

6. DeHaan JD (2007) Kirk's fire investigation, 6th edn. Pearson Education, Inc., Upper Saddle River
7. NFPA (2011) Gasoline at home fact sheet. National Fire Protection Association (NFPA). http://www.nfpa.org/categoryList.asp?categoryID=302. Accessed 4 April 2011
8. Yockers JR, Segal LS (1956) Cigarette fire mechanisms. NFPA Q 49:213–222
9. Stresse G (1970) Zundmoglichkeit von brennbaren Gasen und Dampfen durch glimmenden Tabak. Sonderdruck aus Bundesarbeitsblatt—Fachteil Arbeitsschutz 3:66–70
10. Hagimoto Y, Kinoshita K (1981) Ignition possibility of inflammable mixtures with burning cigarettes. J Jpn Soc Saf Eng 20:197–202
11. Hards DL (1983) Examination of the effect of lighted cigarettes on flammable vapour–air mixtures. Section Paper: IR/L/IN/83/1. Health and Safety Executive, Harpur Hill
12. Holleyhead R (1996) Ignition of flammable gases and liquids by cigarettes : a review. Sci Justice 36:257–266
13. Schuh DA, Sanderson JL (2008) Gasoline vapor testing: what makes a competent ignition source?. Fire Find 16(1):1–3
14. Jewell RS, Thomas JD, Docids RA (2011) Attempted ignition of petrol vapour by lit cigarettes and lit cannabis resin joints. Sci Justice 51:72–76
15. Geiman JA, Fuss SP (2013) Investigation of cigarettes as an ignition source for Coleman fuel. In: Proceedings of the fire and materials 2013 conference. Interscience Communications Ltd., London, pp 759–768
16. Colonna GR (2010) Fire protection guide to hazardous materials, 14th edn. National Fire Protection Association (NFPA), Quincy
17. Colwell JD, Reza A (2005) Hot surface ignition of automotive and aviation fluids. Fire Technol 41(2):105–123. doi:10.1007/s10694-005-6388-6
18. Davis S, Kelly S, Somandepalli V (2010) Hot surface ignition of performance fuels. Fire Technol 46(2):363–374. doi:10.1007/s10694-009-0082-z
19. Shaw A, Epling W, McKenna C, Weckman B (2010) Evaluation of the ignition of diesel fuels on hot surfaces. Fire Technol 46(2):407–423. doi:10.1007/s10694-009-0098-4
20. Drysdale D (2011) An introduction to fire dynamics, 3rd edn. Wiley, West Sussex
21. Glassman I (1997) Combustion, 3rd edn. Academic Press, San Diego, p. 345
22. Maxwell JC (2010) The Maxwell report: year end and fourth quarter 2009 sales estimates for the cigarette industry. John C. Maxwell, Jr., Richmond
23. Ohlemiller TJ, Villa KM, Braun E, Eberhardt KR, Harris RH, Lawson JR, Gann RG (1995) Quantifying the ignition propensity of cigarettes. Fire Mater 19:155–169
24. Ohlemiller TJ, Villa KM, Braun E, Eberhardt KR, Harris RH Jr, Lawson JR, Gann RG (1993) Test methods for quantifying the propensity of cigarettes to ignite soft furnishings, NIST Special Publication 851. National Institute of Standards and Technology, Gaithersburg
25. Friedman R (1998) Principles of fire protection and chemistry, 3rd edn. National Fire Protection Association (NFPA), Quincy
26. Crowl DA (2003) Understanding explosions. Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York
27. Popper K (2010) The logic of scientific discovery. Routledge Classics, New York, pp 266, 375