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Case study: Flame arresters and exploding gasoline containers

Lori C. Hasselbring *

Stress Engineering Services Inc., 13800 Westfair East Drive, Houston, TX 77041, USA

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Abstract

This paper describes the case study of a portable plastic gasoline container explosion and fire. While working at home on a science project to determine the burn rates of different types of wood fuel, a 14-year-old boy was severely burned after flames traveled back up into the portable gasoline container and exploded. A witness heard the explosion and reports that the flames went perhaps 10 ft in the air. It is shown by experimentation that a flame arrester installed in the pour opening of the portable gasoline container would have prevented an explosion inside the gasoline container.

Keywords: Fire; Explosion; Gasoline; Flame arrester

1. Background

In this incident, a 14-year-old boy was severely burned while working at home on a science project to determine the burn rates of different types of wood fuel. Police investigation revealed that the fire was started by a vapor fumes explosion.

Prior to the fire, the boy dug a pit and put rocks around it. He placed crumpled paper and three different types of wood in the fire pit, and used a cigarette lighter to light the paper. He kept adding paper because the wood had not yet caught fire. He then walked over to his house and picked up a gasoline container. The boy estimated that the 5-gal gasoline container weighed "probably a little more than a gallon of milk." The boy stated that there was "a really small flame" in the fire pit when he went to pick up the gasoline container. He intended to pour gasoline on the wood to help it catch fire. He did not remember anything after he picked up the gasoline container and tilted it toward the pit. The next thing he remembered was waking up on the ground with his legs on fire.

A neighbor across the street heard the explosion, followed immediately by the sound of someone screaming in pain. He saw the boy, on fire from head to toe, running across the yard. The flames went perhaps ten feet in the air. While family members took care of the boy, the neighbor set about extinguishing the fire. He reported some surface fire on the boy's house and on the house next door, which he assumed to be gasoline, and which appeared to be already diminishing. He reported considerable fire in leaves and debris in the area between the houses and against the wall of a shed appended to the house next door. The neighbor stated, "What remained of the plastic gasoline can was near the house and was still dripping gasoline, so I moved it to a more central location, away from the two houses and from any combustible materials."

Fire department units arrived shortly after the incident, and extinguished the burning gasoline can and a small area of burning leaves. The fire department report describes the cause of the incident as: "Accidental flammable ignition of a gas can to exposed flame causing the can to explode splattering the victim with gas and flame." The boy was burned over 65% of his body, and suffered permanent hearing loss in his right ear.

2. Explosion definitions

There are several definitions of an explosion. The dictionary defines an explosion as: (1) bursting noisily, (2) undergoing a rapid chemical or nuclear reaction with the production of noise, heat and violent expansion of gases, and (3) bursting violently as a result of pressure from within.

A more scientific definition is given by Strehlow and Baker: "In general, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source. This energy may have originally been stored in the system in a variety of forms; these include nuclear, chemical, electrical or pressure energy for

* Tel.: +1 281 955 2900; fax: +1 281 955 2638.
E-mail address: lori.hasselbring@stress.com.

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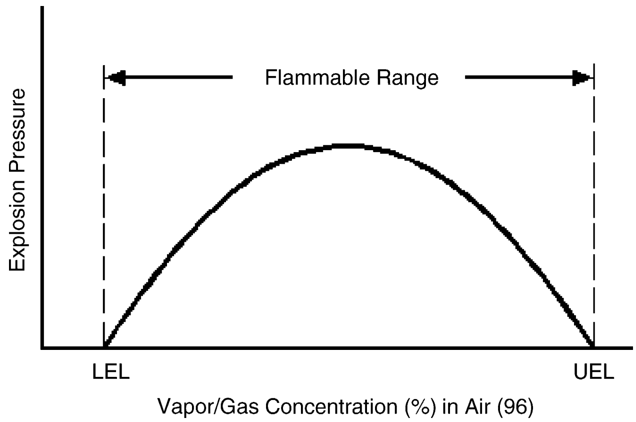

Fig. 1. Flammable range of gasoline.

example. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that external damage be produced by the explosion. All that is necessary is that the explosion is capable of being heard [1].”

According to NFPA 921: “An explosion is a physical reaction characterized by the presence of four major elements: high pressure gas, confinement or restriction of the pressure, rapid production or release of that pressure, and change or damage to the confining (restricting) structure.” An explosion is almost always accompanied by the production of a loud noise. NFPA 921 also gives the following example: “The ignition of a flammable vapor/air mixture within a can, which bursts the can or even only pops off the lid, is an explosion [2].”

For the purposes of this article, an explosion refers to the rapid release of burning gasoline from a gasoline container accompanied by a loud noise.

3. Physical properties of gasoline

Gasoline is a hydrocarbon mixture refined from petroleum. The liquid phase does not burn – only the vapors do. Gasoline has a flash point of $-45\,^{\circ}$F and an autoignition temperature of $495\,^{\circ}$F [3,4]. The molecular weight (and vapor density) of gasoline is about 3.4 times that of air. Thus, gasoline vapors tend to stay near ground level and move around and spread out under the influence of air currents and the confinement of walls.

The explosive range (or flammable range) of gasoline is between 1.4 and 7.6% volume in air [5,6]. Below the lower explosive limit (LEL), there is not a sufficient concentration of vapors in the air to permit propagation of a flame upon contact with an ignition source. Above the upper explosive limit (UEL), there is too great a concentration of vapors in the air to permit propagation of a flame. See Fig. 1.

4. The history of flame arresters

Sir Humphrey Davy developed the first miner’s flame safety lamp in 1815 [7]. The Davy lamp focused on a safe way to provide lighting for coal miners, and involved the use of a perforated metal barrier to prevent the propagation of a flame through a flammable vapor mixture. The gauze of the lamp commonly used contains about 26 apertures in the length of 1 in. or 676 in the square.

The principle of the Davy lamp has been utilized in various patent applications over the past two hundred years. The first U.S. patent for a spark arrester was granted to O.S. French and J.W. Miller on June 19, 1906 [8]. The spark-arrester invention was particularly adapted for traction-engines, although applicable to locomotives or stationary engines.

During the early 1930s, R.J. Anschicks, assignor to Protectoseal Company, developed and patented a tank fitting that incorporated a flame arrester [9]. This fitting was used to protect large atmospheric storage tanks in the petroleum and petrochemical industries from fire and explosion. All gasoline containers currently manufactured by the Protectoseal Safety Container Division have perforated metal flash arresters positioned at each container opening.

Currently, flash arresters are usually manufactured from light gauge perforated metal. The thickness of the metal and the size and location of the perforations are carefully chosen to insure that effective protection against flame propagation is achieved. The flash arrester design allows liquids and vapors to pass through (that is, flow through the perforations) but provides a barrier to flame passage if the vapors on one side of the arrester should be ignited. The flash arrester absorbs and dissipates the heat generated by the flame. It insures that the vapors on the protected side of the flash arrester barrier do not reach their ignition temperature [10–12].

In modern industry, the use of flame arresters is diverse. Flame arresters are commonly installed at the fuel tank opening of gasoline- or diesel-powered industrial trucks and equipments, including forklift trucks, tractors, and airport utility vehicles. Flame arresters are also installed on storage tank nozzles or in flammable vapor piping systems or in flare stacks, in chemical, petrochemical, petroleum and pharmaceutical plants where the storage, transfer, and collection of flammable liquids are part of their daily operation.

According to federal requirements regarding boating safety, “Gasoline engines installed in a vessel after April 25, 1940, except outboard motors, must be equipped with an acceptable means of backfire flame control. The device must be suitably attached to the air intake with a flame tight connection and is required to be Coast Guard approved or comply with SAE J-1928 or UL 1111 standards and marked accordingly.”

On National Forest lands, spark arresters must be installed on all internal combustion engines such as four-wheelers, motorcycles, and chainsaws, since a properly operating spark arrester prevents accidental wildfires.

One of the most recent applications of the flame arrester is the Flame Guard® Safety System introduced by the American Water Heater Company in 1999 [13]. This technology has been proven to reduce the risk of home fires from flammable vapors coming in contact with a gas water heater’s burner or pilot light.

5. Discussion of portable gasoline containers and flame arresters

In May 1973, *Consumer Reports* concluded that all but two of the nineteen models of portable gasoline containers tested had major safety shortcomings [14]. “Should fumes outside the can ignite as you pour or fill, a flashback is possible that could ignite the contents of the can itself. Such accidents can be prevented by a flame-arrester, which we think should be legally required in all openings of containers like these. As it is, only the makers of the Jerry Jug and the Eagle Safety have bothered to provide an arrester.”

In March 1981, Consumer Reports tested and rated 25 models of portable gasoline containers [15]. The article stated, “Pouring gasoline in the presence of even the smallest open flame is asking for trouble. Should the gasoline ignite, flames could race up the stream of fuel and into the container, causing a devastating explosion. A flame arrestor – a fine wire mesh in the pour opening – can prevent this hazard. In this group, only the safety cans and the Kidde Explosafe models have a flame arrester. All should.”

It is not surprising that all metal safety cans currently on the market have flame arresters installed since these are required for Factory Mutual approval [16]. However, no manufacturers of portable plastic gasoline containers have voluntarily installed flame arresters, and there are currently no regulations requiring them to do so [17–25].

6. Static fire tests

Table 1 lists static fire tests conducted in a firebox at Stress Engineering Services, Inc. designed to verify the explosive range reported for gasoline, that is, 1.4 to 7.6% gasoline vapors in air. The amount of liquid gasoline added to a 5-gal gasoline container was varied from 2.25 to 13. 5 ml to vary the concentration of gasoline vapor in air from 2.5 to 15%, respectively. Theoretically, addition of 4.5 ml (or about one teaspoon) liquid gasoline to a 5-gal container of air will result in about 5% gasoline vapors in air assuming that all of the gasoline is vaporized, which should result in an explosion inside the gasoline container.

The static fire tests were conducted with a 5-gal portable plastic gasoline container without a spout. Before adding gasoline, the container was purged with high-pressure air for five to ten minutes. A length of cotton wick was soaked in gasoline (in order to produce a larger flame), and a small bit of modeling clay was used to position the wick in the pour opening of the gasoline container. A butane fireplace lighter was used to safely light the wick extending out of the container.

At 15% gasoline vapor in air (13.5 ml liquid gasoline), the mixture was too rich to burn and the flame burned above the pour opening and did not enter the gas container. At 2.5% gasoline vapor in air (2.25 ml liquid gasoline), the mixture was too lean to burn and the flame self-extinguished in the gas can.

These fire tests demonstrated that explosions occurred at 5 to 10% gasoline vapor concentration, that is, when 4.5–9 ml liquid gasoline was added to the 5-gal container. These explosions consisted of a whooshing noise as flame and gasoline spewed out the pour opening. The force of the explosions moved the gasoline container about 3–6 in. backward. However, when a brass wire mesh flame arrester was installed in the pour opening of the gasoline container, there was no explosion, even though gasoline vapors above the flame arrester continued to burn until extinguished.

7. Gasoline spill tests

Table 2 lists gasoline spill tests conducted in a firebox at Stress Engineering Services, Inc. to determine the effectiveness of flame arresters installed in portable plastic gasoline containers. These tests were documented by videotape.

An individual wearing fire-resistant personal protective equipment spilled gasoline from a 5-gal portable plastic gasoline container near a fire contained in a dirt pit. The variables tested include a gasoline container with and without a flame arrestor, with and without a spout, the amount of gasoline spilled, and the ignition source.

Fire tests conducted with one-half to two cups of gasoline added to the gasoline container resulted in a concentration above the explosive range of gasoline, and the flame typically burned above the pour opening. However, in two out of three spill tests, as liquid gasoline was poured near burning paper or propane, air entered the gasoline container until the gasoline-to-air ratio was within the explosive range, and resulted in spraying burning gasoline outside the dirt pit.

Fire tests were also conducted with much smaller amounts of gasoline (15–30 ml) to produce the explosive gasoline vapor concentrations determined experimentally in the static fire tests. In all but one of these tests, the explosion occurred soon after the individual had finished spilling the gasoline and was holding the gasoline container right side up.

Table 1
Gasoline container static tests

Fire test	Gas can description	Flame arrester	Amount of gasoline (ml)	Ignition source	Explosion
1	5 gal without spout; vent open	No	13.5	Wick	No
2	5 gal without spout; vent open	No	9	Wick	Yes
3	5 gal without spout; vent open	No	4.5	Wick	Yes
4	5 gal without spout; vent open	No	4.5	Wick	Yes
5	5 gal without spout; vent open	No	2.25	Wick	No
6	5 gal without spout; vent open	Yes	4.5	Wick	No
7	5 gal without spout; vent open	Yes	4.5	Wick	No

Table 2
Gasoline spill tests

Fire test	Gas can description	Flame arrester	Amount of gasoline	Ignition source	Explosion
1	5 gal with spout; vent open	No	2 cups	Paper	Yes
2	5 gal with spout; vent open	No	1 cup	Paper	Yes
3	5 gal without spout; vent open	No	1/2 cup	Paper	No
4	5 gal without spout; vent open	No	15 ml	Paper	Yes
5	5 gal without spout; vent open	No	15 ml	Paper	No
6	5 gal without spout; vent open	No	15 ml	Paper	Yes
7	5 gal without spout; vent open	No	20 ml	Propane	Yes
8	5 gal without spout; vent open	No	30 ml	Propane	Yes
9	5 gal without spout; vent open	No	25 ml	Propane	Yes
10	5 gal without spout; vent open	Yes	20 ml	Propane	No
11	5 gal without spout; vent open	Yes	15 ml	Propane	No
12	5 gal without spout; vent open	Yes	30 ml	Propane	No

Similar fire tests (using 15–30 ml gasoline) were conducted with the exception that a brass wire mesh flame arrester was installed in the pour opening of the gasoline container. In all cases, as gasoline was spilled near the lit burner, vapors above the pour spout ignited and continued to burn until self-extinguished. There was never an explosion in the gasoline containers with flame arresters.

8. Summary

1. Fire and police incident reports in this case study indicate that gasoline vapors in the portable plastic gasoline container ignited and exploded, resulting in burns over sixty-five percent of the boy's body. The boy also suffered permanent hearing loss in his right ear. A flame arrester installed in the pour opening of the gasoline container would likely have prevented the incident.
2. A sketch in the police incident report shows a burning spray pattern in all directions 12–15 ft away from the original fire pit location. This sketch shows evidence of fire on the neighbor's house located west of the fire pit. Also, east of the fire pit, there was evidence of burnt leaves around the lawn mower and melted garbage bags and a melted blue tarp located next to the boy's house. However, there was little fire damage in the immediate area surrounding the fire pit. The burning gasoline spray was likely due to the force of an explosion inside the gasoline container.
3. There are a number of variables that contribute to whether or not a gasoline container will explode. In order for an internal explosion or fire to occur, the atmosphere within the container must be within the lower and upper flammability limits of gasoline in air, theoretically, between 1.4 and 7.6%. Although the boy does not know how much gasoline was in the 5-gal container, he estimates that it was 1 gal. This incident is just one of many subjects of lawsuits in which explosions have been reported for gasoline containers containing more than the calculated explosive amount of gasoline. It is significant to note that these explosions almost always occur as gasoline is being poured or sloshed around [26]. This suggests that air is drawn into the gasoline container through the vent or spout, which results in transient changes in the gasoline-to-air ratio to bring it within the flammability range at some point in location and time within the gasoline container.
4. It has consistently been the observation of investigators that "ignition is, by nature, a statistical event, in terms of time, location, and controllable conditions due to microscopic chemistry and other factors [27]." Known ignition variables include temperature, humidity, wind speed, amount of gasoline in the can, winter versus summer blends of gasoline, elevation of the can, whether or not pouring out of the can is taking place, how much gasoline has been spilled outside of the can, the location and intensity of the ignition source with respect to the can, whether or not gasoline that has been spilled is on an absorbent surface such as dirt or a surface such as concrete that will allow the gasoline to spread, and the exact sequence of events leading to any particular incident. With all these variables, it is difficult to determine combinations of them that may lead to a gasoline container explosion.
5. Fire tests conducted as Stress Engineering Services Inc., demonstrate a burning gasoline spray from a 5-gal plastic gasoline container consistent with the description given in police and fire incident reports for the abovementioned case study.
6. Fire tests conducted at Stress Engineering Services Inc. demonstrate that a flame arrester installed in a portable plastic gasoline container prevents an explosion inside the gasoline container. Flame arrester technology dates back to 1815, and flame arresters are currently installed on all safety gasoline containers.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2005.07.040.

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