Portable Plastic Gasoline Container Explosions

And

Their Prevention

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Abstract

The work described in this report was undertaken to determine probable causes of portable plastic gasoline container explosions and to consider and demonstrate preventive technologies for such explosions. Dozens of explosions with this class of containers have been reported in newspapers, legal briefs as well as in fire incidence and peer-reviewed engineering literature.

Fresh conventional gasoline stored in portable plastic containers has an associated headspace which is sufficiently rich in hydrocarbon vapors to prevent ignition from random ignition sources. However, since fresh gasoline evaporates readily, and the lighter ends of these gasoline blends of common hydrocarbons evaporate preferentially, a working hypothesis considered in this work has been that given adequate time, such a vapor space filled by vapors from commercial gasoline blends will eventually fall into the explosive range as more volatile fractions evaporate.

No comprehensive test program demonstrating how and when such processes occur has been published to date. This report provides preliminary results for such a test program pending their further dissemination.

Results presented here clearly show that when gasoline aging occurs [evaporation and diffusion of lighter ends through openings of portable plastic gasoline containers], ambient temperature and volume of aged gasoline in the container are primary variables controlling when explosions can occur.

Additional data is provided demonstrating how simple inexpensive flame arrester designs fitted to gasoline containers can prevent such accidents.

1. Background

Explosions and explosion-like events associated with pouring gasoline from a partially filled, portable, plastic gasoline container have been reported as discussed in this paper. More frequently than not, when such events are reported, they have resulted in serious injuries to individuals participating and nearby. Most of the incidents have involved the burning of trash and more specifically pouring of gasoline from the can onto fire debris in an attempt to restart a fire thought to have burned out.[1] Similar mishaps resulting in injuries are reported in the accident and fire incidence literature and in reports from Federal agencies.[2]

It is the objective of this paper to review the occurrence of such incidents, characterize the physics associated with their occurrence and consider possible mitigation features such as flame arresters in the containers to reduce or eliminate these occurrences.

A review of peer-reviewed articles in engineering and fire science journals revealed one on-point article, published in the *Journal of Hazardous Materials*, by Lori Hasselbring.[3] Hasselbring's research and testing indicated that such phenomena are real, but her research was limited in terms of explaining how and why gasoline container explosions occur. Air entrainment during pouring was suggested as one possible explanation.

More general comments can be found in fire science texts suggesting both that portable plastic gasoline container explosion events *do* occur and that they *do not* occur. The *Ignition Handbook* is one example, with the book suggesting

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[1] Wibbenmeyer, Lucy A. MD, FACS; Kealey, Gerald P. MD, FACS; Young, Tracy L. MS; Newell, Ingrid M. MD, BS; Lewis, Robert W. II PA-C; Miller, Benjamin R. BS; Peek-Asa, Corrine PhD, "A Prospective Analysis of Trash, Brush and Grass Burning Behaviors," Journal of Burn Care & Research, May/June 2008 – Volume 29, Issue 3, pp 441-445.

[2] Consumer Product Safety Commission, National Electronic Injury Surveillance System, CPSC Document #3002, http://www.cpsc.gov/cpscpub/pubs/3002.html. National Fire Incident Reporting System, Department of Homeland Security, http://nfirs.fema.gov.

[3] Lori Hasselbring, "Case Study: Flame Arresters and Exploding Gasoline Containers," Journal of Hazardous Materials 17 Mar. 2006: 64–68.

gasoline container explosions can happen while a *Corrigenda* to the original volume provided by the author on the internet states otherwise.[4] However, no references are provided to any significant testing or analysis for either condition, and as such, neither claim should be considered persuasive.

The National Bureau of Standards (NBS) has commented in its reporting that gasoline can explosions can occur and the use of flame arresters in the spout can prevent such explosions.[5,6] The National Bureau of Standards (NBS) is the predecessor to the National Institute of Standards and Technology (NIST).

Consideration of such explosions in anecdotal forums is common. For example, the *Consumer Reports* has commented on this subject on two occasions. [7] Newspaper and television reports often quote witnesses describing an explosion sound and in at least one case a plastic gasoline can was produced clearly showing material tearing behavior consistent with an explosion.[8] (See figure 1.)

This investigation began by developing a method to measure the hydrocarbon concentration in the head space of a gasoline can to allow the assessment of various causes of an explosion. The gasoline used in the testing described in this paper was commercial grade 87 octane, California winter blend. It should be noted that winter blend gasoline in a plastic can, with few openings and closings, quickly ages to and its properties asymptotically approach those of summer blend gasoline. Thus, the authors would expect no significant differences with summer gasoline.

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[4] Vytenis Brabrauskas Ph.D., Ignition Handbook, (Issaquah, WA: Fire Science Publishers, 2003); Corrigenda to Ignition Handbook 2008, http://www.doctorfire.com/corrigenda.pdf.

[5] Tyrell, E., 1975. “Gasoline and Gasoline Container Fire Incidents,” NBS Technical Note 850.

[6] Jones, C.E., 1977. “Standards for Gasoline and Kerosene Cans,” NBSIR 78-1414.

[7] “Gasoline Cans,” Consumer Reports May 1973: 332-335; “Gasoline Containers,” Consumer Reports March 1981: 168-171

[8] Fox 25 News, Boston, “Fire pit explosion critically burns man”, 20 Jun 2009, 3 Nov 2009 < http://topics.myfoxboston.com/m/23142009/fire-pit-explosion-critically-burns-man.html.

Figure 1. Subject gasoline can showing clear signs of explosion and rupture.

2. Measurement of Hydrocarbon Vapor Concentrations

Oxygen sensors are used in many applications to measure volumetric percent hydrocarbon in a vapor solution, such as a container headspace. Such a methodology is described by Shirvill, et. al[9] and the same basic method was used in this study. The concentration of gasoline vapors is obtained from a pair of readings using a City Technologies oxygen sensor which provides a 0-10 volt output corresponding to 0 to 30% oxygen. The first reading, V_0, measures the partial pressure of oxygen in air. The second reading, V, measures the partial pressure of oxygen in the mouth of the gasoline can. The percent volumetric concentration of gasoline, Pg, in the mouth of the can is given by:

$$Pg = 100\ (V - V_0)/\ V_0.$$

Use of this method allowed hydrocarbon concentrations in the headspace to be directly measured in the gasoline cans used. Example measurements of fresh gasoline and lightly aged gasoline (1 liter of gasoline left for 8 hours in a 30.5 cm diameter bucket, outdoors, 10 ^oC average temperature, and 8 ^oC

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[9] L.C Shirvill, P. Roberts, C.J. Butler, T.A. Roberts and M. Royle, "Characterization of the Hazards from Jet Releases of Hydrogen," International Conference on Hydrogen Safety (Pisa, Italy, September 8-10, 2005.)

temperature range) are shown in figure 2. The light “bucket” aging was roughly equivalent to aging for 5 days in a typical 18.9 liter (5 gallon) plastic gasoline container with a 1.9 cm diameter open nozzle at an average 10 ^oC with a 16 ^oC range. These results illustrate the interrelationship between aging, temperature, and amount stored in a given volume, as well as the relationship of these variables to the commonly accepted UEL for common gasoline blends.

The results clearly show that the percent hydrocarbon in a gasoline can and propensity to explode, is a function of aging, temperature and quantity.

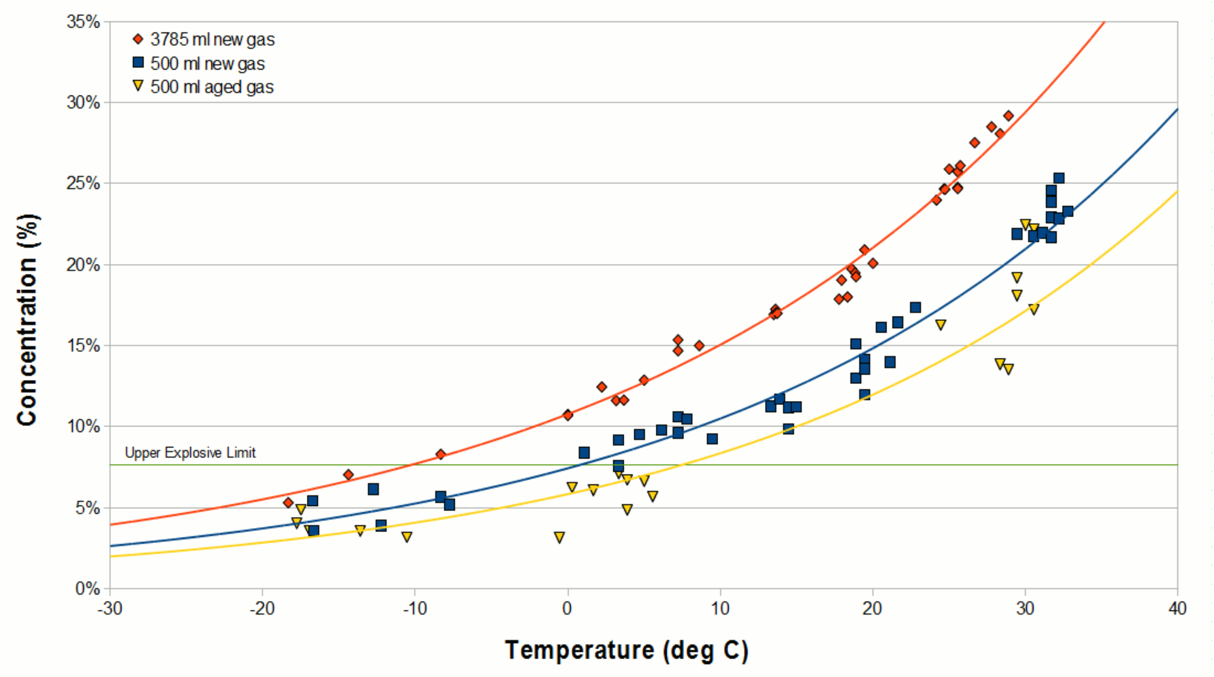

Figure 2. Hydrocarbon vapor concentration in a 18.9 liter (5 gallon) gasoline can for fresh and lightly aged gasoline (aged in an open bucket equivalent to 5 days at 10 ^oC in a typical 18.9 liter gasoline container with an open spout).

The data shows that the hydrocarbon vapor concentration of lightly aged gasoline can easily fall below the upper explosive limit for lower temperatures and smaller amounts of liquid fuel in the can. It should be noted that it is common in explosion incidents investigated by the authors that the subject gasoline can was left open for weeks or months prior to the incident. The data also shows that smaller amounts promote accelerated aging as the ratio of liquid fuel surface area to volume is increased, resulting in an increased evaporation and diffusion rate per volume.

3. Gasoline Aging

Aging of gasoline is a relevant and important process in these discussions because aging of fresh gasoline is a precondition for a gasoline container explosion. If there is no aging, the hydrocarbon concentration in the vapor space will be above the upper explosive limit and neither ignition nor explosion can occur.

Like most liquids, gasoline will evaporate if left in an open container. Gasoline contains a range of lighter and heavier hydrocarbon constituents, typically with between 4 and 12 carbon atoms per molecule.[10] The so-called "lighter ends," which are lower molecular weight fractions, evaporate preferentially from such an open container, lowering the gasoline's hydrocarbon vapor pressure with time. This process is what we refer to here as "aging."

It is also well known, based on research related to air pollution considerations, that component fractions of gasoline will diffuse across the walls of a standard plastic gas can. In such cases, the rate of this diffusion is inversely proportional to the molecular weight of the hydrocarbon fraction involved, and directly proportional to the flux gradient of any given fraction; i.e. the greater the difference in concentration of a given fraction across the container wall, the greater the diffusion rate.[3]

The authors performed aging tests with gasoline blends stored in plastic cans with their spouts left open. The resulting changes in vapor concentrations in the headspace of these cans over time were measured and are shown in figure 3 below. The data show a relatively sharp drop in vapor concentration in the headspace followed by a decreasing rate of change in concentrations.

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[10] Chris Collins, "Implementing Phytoremediation of Petroleum Hydrocarbons," Methods in Biotechnology 23, ed. Neil Willey (Totowa, NJ: Humana Press, 2007).

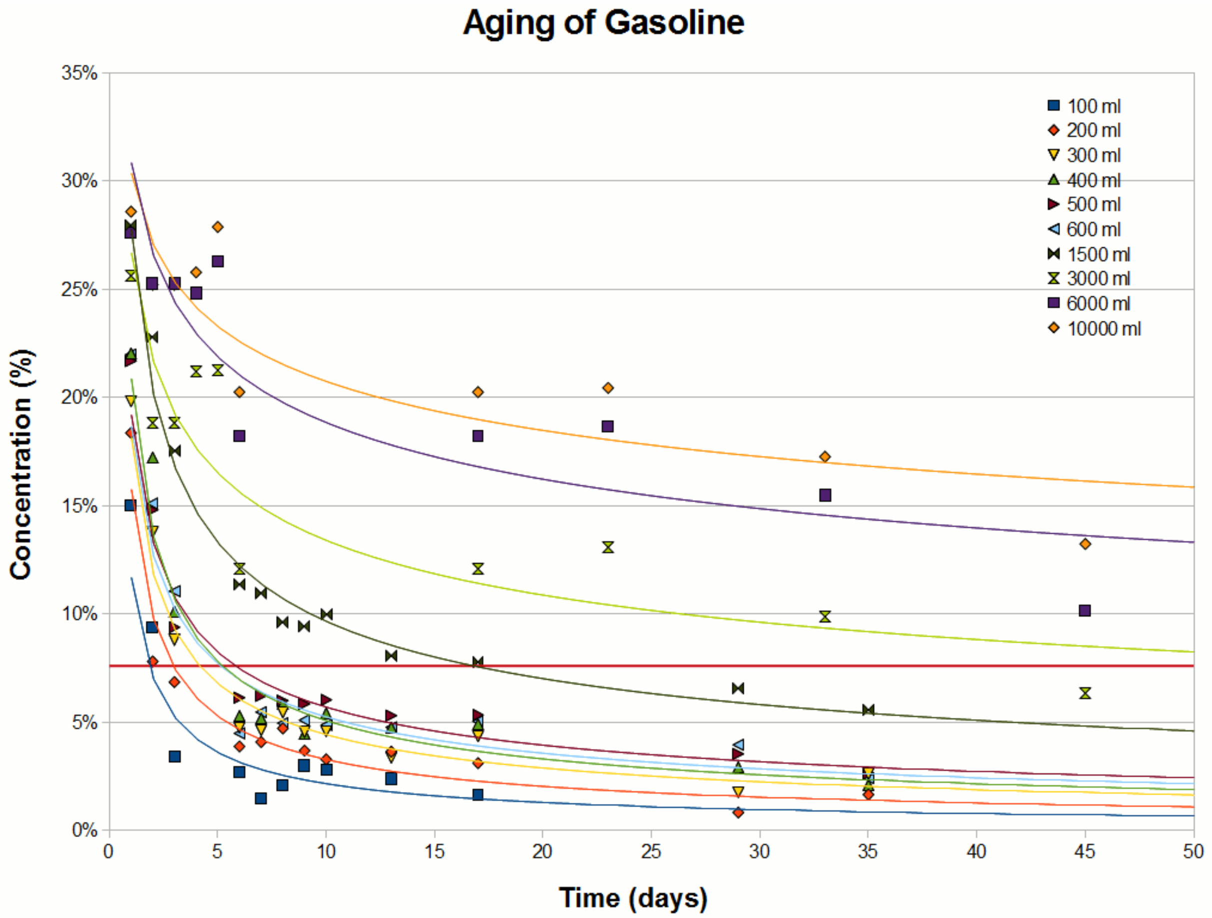

Figure 3. Aging results for commercially obtained 87-octane gasoline stored outdoors, average temperature of approximately 10°C, 16°F average daily range, in a Blitz 18.9 liter gasoline can (19 cm by 38 cm base, 63.5 cm tall). Starting volumes ranged from 100 ml to 10 liters.

The gasoline aging data presented above is quite similar to data published recently by Japanese researchers in the *Fire Safety Journal.*[11] The light ends evaporate preferentially and the headspace hydrocarbon vapor pressure and volumetric percent hydrocarbon drops with time.

As shown in figure 3, gasoline vapor pressure percent hydrocarbon is lower for decreasing temperature and decreasing amounts in a container. As an example, for 1.5 liters of gasoline stored in an open 18.9 liter can at an average

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[11] Katsuhiro Okamoto, Norimichi Watanabe, Yasuaki Hagimoto, Koji Miwa, Hideo Ohtani, "Changes in Evaporation Rate and Vapor Pressure of Gasoline with Progress of Evaporation," Fire Safety Journal 44, July 2009: 756-763.

temperature of 10 ^{o}C (16 ^{o}C average temperature range) the percent hydrocarbon in the vapor headspace falls into the explosive range in less than 20 days. The Blitz 18.9 liter can was used for the aging studies.

4. Computational Fluid Dynamics Analysis

It was theorized by Hasselbring[1] that air entrainment during pouring might be responsible for the vapor headspace dropping below the upper explosive limit (UEL) and thereby creating an explosive hydrocarbon/air mixture. In order to test this potential contributing factor, pour tests were conducted initially with measurement of the vacuum produced in the can. This simple "monometer testing" was followed by a computational fluid dynamics (CFD) analysis using the multi-physics finite element program, COMSOL.[12]

The apparatus for monometer testing and the results are shown in figure 4a 18.9 liter plastic gasoline storage can was filled with liquid, placed on a scale, and tipped such that the liquid poured out while the manometer and scale were both captured on video to document the negative internal pressure simultaneously with the change in mass (which relates directly to the liquid flow rate). These tests (can tipped 90 degrees) show that a significant negative internal pressure can occur in a gasoline can in the range of 15-18 cm of water column (1.5-1.7 kPa) during pouring. Interestingly, this depression is of approximately the same magnitude as the positive pressure in a typical gas stove or heater burner manifold. It is also more than adequate to cause airflow into such a can during pouring.

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[12] COMSOL Multiphysics Modeling and Simulation Software, http://www.comsol.com/.

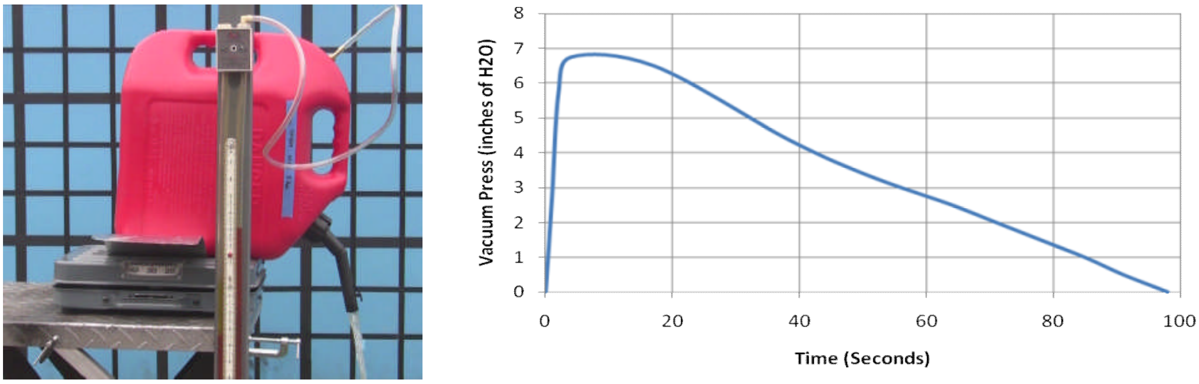

Figure 4. Gas can connected to a monometer (left) and typical time vacuum pressure as a function of time curve (right).

The maximum or worst case negative pressures from the pouring tests were used as inputs for the COMSOL finite element analysis. The results further confirmed that air entrainment can and does lower the percent hydrocarbon in a gasoline can vapor space during pouring. However, with all but the smallest amount of gasoline being stored in such a container, some combination of aging, temperature reduction and/or low volume amount in the can is still required for the vapor space to be in the explosive range. For example, at -9.1 °C, the percent hydrocarbon must be 13% or lower to produce an explosive mixture (percent hydrocarbon below the upper explosive limit) in the can due to air entrainment. This would have to be significantly aged gasoline as the percent hydrocarbon in the head space for fresh gasoline is approximately 35%. Air entrainment is a complex effect that we are continuing to study.

Modeling 30 seconds of pouring requires several days of computer time even with fast, multi-processor computers. Figure 5 below is a graphic representation from one modeling run illustrating the relationship between pouring and air entrainment.

Figure 5. Lines of flow (red streamlines) show the motion of vapor, and partial vapor pressure/gasoline vapor concentration (color contours) show the variation of gasoline vapor concentrations inside a 18.9 liter (5 gallon) can during pouring with aged gasoline.

5. Explosion Testing

Field evidence and aging tests and calculations indicate that gasoline can explosions can and do occur under foreseeable conditions when their concentration is below the upper explosive limit UEL (7.6%) and above the lower explosive limit LEL (1.4%).[13] However, given the skepticism as to the occurrence of such events in some literature, it was decided to conduct explosion testing to verify the reported events under reproducible conditions.

In these tests, measured amounts of gasoline samples were added to the container, and the container was inverted as in pouring, which mimics the most common scenario for incidents reported from the field. Inversion of the can was accomplished using a test jig in a reinforced test cell. The open spout

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[13] David R. Lide, ed., CRC Handbook of Chemistry and Physics, 90th ed. (Boca Raton, FL: CRC Press; 2009-2010); "Material Safety Data Sheet (MSDS)," 30 Oct. 2008, http://www.msdssearch.com.

was sited near an ignition port and a small flame was passed near the spout as shown in Figure 6.

The explosion tests were initially conducted using 18.93 liter commercially available gasoline cans with gasoline contents ranging from 20 to 1,750 ml in various degrees of aging. In addition, tests with 7.85 liter (2 gallon) containers were also conducted.

Most tests were run using cans modified to provide explosion relief using plastic plugs, as seen in figures 6 (below). This prevented the type of excessively violent explosions which had occurred in some of the cases studied, thus avoiding a safety hazard and/or excessive property damage.

Figure 6. Gasoline cans tested w/o flame arresters from 4 separate tests with gasoline in the explosive range.

Confirming the need for such explosion relief, tests were also performed with gasoline cans in the as-is state, *without* the pressure relief port. Typically, the cans ruptured from the overpressure as shown in figure 7 below:

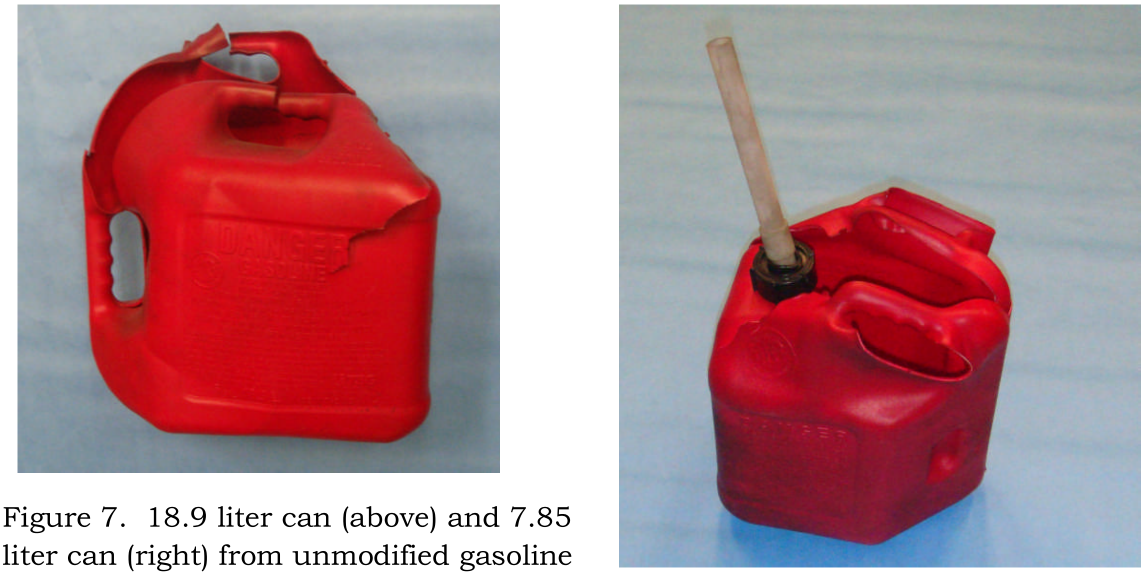

Figure 7. 18.9 liter can (above) and 7.85 liter can (right) from unmodified gasoline can explosion tests.

The ignition process leading to the overpressure conditions in the portable plastic gasoline containers is also being studied. In this case, the travel of a flame front can be observed traveling up the plastic spout of the 7.85 liter can (figure 8) using high speed video recording. The published gasoline flame speed of 0.4 meters per second was confirmed.

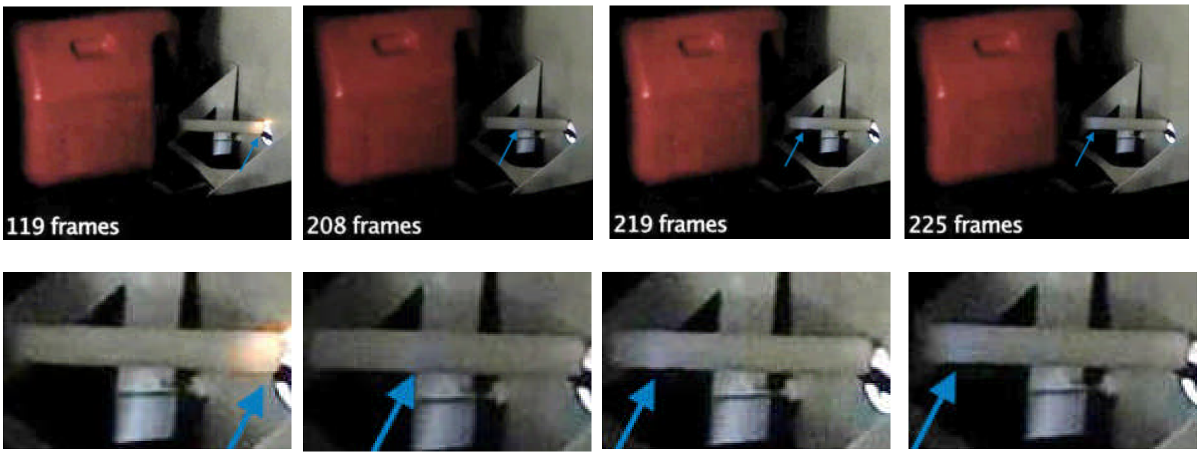

Figure 8. Top row: stills from the video 7.85 liter can tests showing the flame traveling up the translucent plastic spout (blue arrow). Bottom row: blowup of the plastic spout area corresponding to the frame above in the top row.

Over 50 gasoline can explosion tests have been conducted. Plotted relative to the percent hydrocarbon in the vapor space, the results confirm the published upper and lower gasoline explosive limits (figure 9):

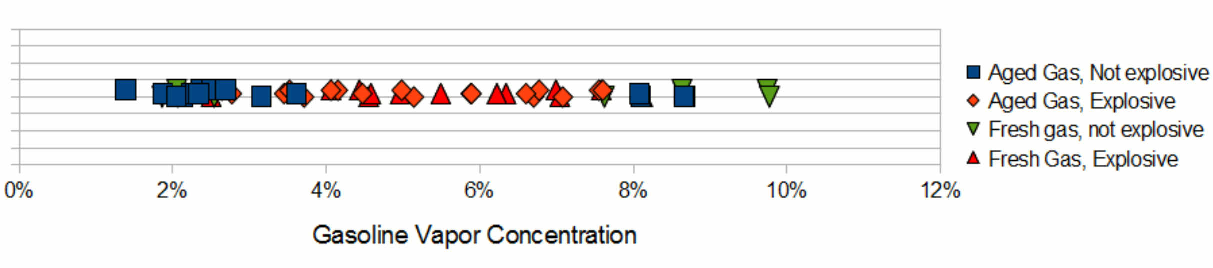

Figure 9. Explosion Go-NoGo tests as a function of percent hydrocarbon concentration. The fresh gasoline data points in the explosive range were created by low temperature. Red and orange points indicate an explosion occurred in the test.

The test results include some No-Go or “not explosive” data points above the lower explosive limit (LEL). It should be noted that the concentration was measured without the spout, a few minutes prior to the time of ignition. During the low concentration tests, the vapor in the spout at the time of ignition may be leaner than the measured value. When the gasoline vapor concentration is low, the diffusion and gross motion of the gasoline vapor/air mix from the can to the spout is slower than for high concentrations. This can lead to a situation where the actual gasoline vapor concentration in the spout is leaner than the LEL, while the value measured is richer.

6. Flame Arresters

Flame arresters have been used industrially for almost two hundred years. Sir Humphry Davy[14] first developed a flame arrester for coal miner lamps in 1815. Patents were issued for flame arresters in the 1880’s for both chemical processes and flammable liquid containers (Allonas 1878).[15] During the early 1930s, R.J. Anschicks, assignor to Protectoseal Company, developed and

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[14] Henry A. Pohs, The Miner’s Flame Light Book: The Story of Man’s Development of Underground Light (Denver: Flame Pub. Co., 1995).

[15] J. Allonas, “Spark-Arrester,” US Patent No. 295716 (July 9, 1878).

patented a tank fitting that incorporated a flame arrester.[16] All gasoline containers currently manufactured by the Protectoseal Safety Container Division have perforated metal flash arresters at each container opening.

A flame arrester works by removing heat from a flame and keeping the temperature of the fuel on the other side of the arrester below its ignition point. The flame arrester mesh breaks the flame into many flamelets, and the heat of these flamelets is transferred to the walls of the mesh. There are two criteria for successful operation: the holes in the mesh must be less than the critical diameter, and the critical velocity must be higher than the flame speed. The critical diameter d_{cr} from Gossel[17] is given by:

$$d_{cr} < 30a/S_u$$

where a is the thermal diffusivity in air (1.0 m^2/s), and S_u is the fundamental burning velocity (0.4 m/s for gasoline), a property of the fuel.[12] The critical velocity, a function of mesh geometry, is also given by Gossel:[17]

$$V = (0.38ay)/d^2$$

where a is the fractional free area of the arrester surface, y is the thickness (width) of the arrester elements (cm), and d is the diameter of the apertures (cm). Gossel presented two different equations for the critical velocity. We are using the more conservative equation (shown above) with a safety factor of 2.5. We have evaluated these criteria for flame arresters in three gas cans using the equations above. The results are given in Table 1 below:

Table1: Flame Arrester Comparisons

Can Material	Name	d - mesh hole size cm	Critical diameter (cm)	y - wire thickness cm	V (m/s)	Gasoline-vapor/air flame speed (m/s)
Metal	JUSTRITE	0.0584	0.3	0.025	1.374	0.4
Plastic	EAGLE TYPE1	0.143	0.3	0.048	0.503	0.4
Metal	Blitz Commercial	0.03	0.3	0.020	3.04	0.4

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[16] Rudolph J. Anschicks, "Filling and Venting Device," U.S. Patent No. 1,814,656, (Assignor to Protectoseal Company of America, July 14, 1931).

[17] Stanley S. Grossel, Deflagration and Detonation Flame Arresters, (New York: American Institute of Chemical Engineers, 2002).

For each of these arresters, the mesh hole size is less than the critical diameter, and the critical velocity is larger than the fundamental burning velocity for gasoline. All of these flame arresters have been successfully tested in gas cans. Blitz states that their screen is meant to be used as a filter, but we have found that it also works as a flame arrester. The flame arrester from the JUSTRITE can is shown below:

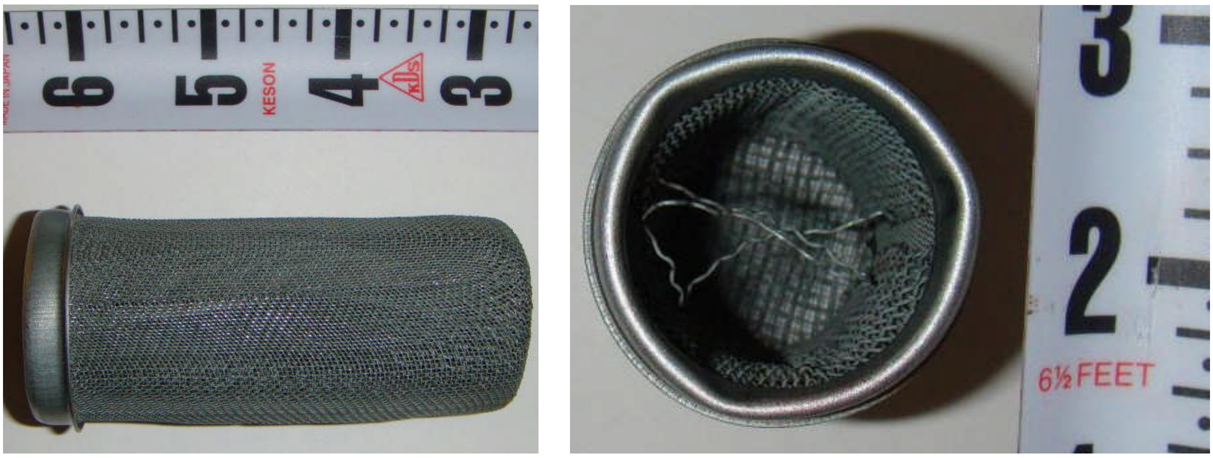

Figure 10. JUSTRITE flame arrester; fits into the can at the spout base.

Fifteen tests were conducted with flame arresters with the same aged gasoline and under the same conditions as tests that produced explosions. Not once did an explosion occur. When measured, the temperature of the flame arrester (installed at the base of the spout and similar in size to the JUSTRITE device) was always found to be elevated near 100°C; the flame had reached the arrester, but could not pass through.

Video still pictures of the explosion tests with flame arrester are uneventful and shown below. Note the test flame at the end of the spout.

Figure 11. Gasoline cans tested with flame arresters exhibited no explosion.

7. Discussion and Conclusions

The extensive testing and analysis performed in this study demonstrate that explosions of gasoline stored in commercially available portable plastic gasoline containers can and do occur. Preconditions for such events are the presence of an open flame or static ignition source and the presence of a vapor space where the percent hydrocarbon concentration is within the explosive range between the accepted upper and lower explosive limits for commercial gasoline blends. Combinations of conditions leading to the vapor space being in the explosive range include aging of gasoline, low ambient temperature and/or a small amount of gasoline remaining in the can.

The testing and analysis also demonstrate that an inexpensive screen flame arrester can prevent these types of event from occurring.