THE NECKED VESSEL FLAME THROWER EFFECT

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ABSTRACT

Fire and explosion incidents involving ignitable liquids carried in and poured from containers have likely occurred for long as mankind has been carrying ignitable liquids in containers. These incidents have taken many forms from simple pool fires to massive explosions. The outcome of each incident is dependent on many variables. Each variable has an effect, and the combination of the different variables can end in a result not always obvious or intuitively expected.

Of the many possibilities involving ignitable liquids in containers, one of late has become a "cause célèbre" and frequent litigation issue. This particular phenomenon is the overpressure expulsion of flaming vapor and liquid from a container the contents of which are being poured onto or near a source of ignition. Lately touted as a "newly realized phenomenon," the forcible ejection of an ignitable liquid is, or at least should be, the recognized result of a container becoming pressurized during the incident and its contents being forced through a narrow opening. This type of container can best be described as a "necked vessel" and the phenomenon as "The Necked Vessel Flame Thrower Effect."

While frequently described as an "explosion", the phenomenon is in fact a poorly understood type of flash fire which can take several different iterations. The outcome of the event – and in fact whether or not the event will even occur – is the result of the interaction of several variables. It is these variables and the results their combinations affect which this paper will address.

The first litigation involving an incident in which burning ignitable liquid was propelled out of a container was filed in Louisville, Kentucky in 1978. Original investigative research discovered that this was a repeatable phenomenon, and the result of the ignitable liquid being poured out of the container into an open bowl already containing an open flame. Burning vapor of the liquid stream transmitted the flame back into the bottle and ignited the vapor/air mixture in the headspace of the bottle. This resulted in a significant overpressure in the bottle which expelled burning vapor and liquid out the spout. This historic case set the stage for future investigations, research and litigation that would follow in its wake.

Recently, some in the field of fire investigation have "rediscovered" the phenomenon and given it new names even though this phenomenon has been known and documented for almost four decades.

In 2013, extensive study and laboratory tests were conducted outside the scope of any specific incident or litigation. The study viewed and evaluated the following variables in producing the "Necked Vessel Flame Thrower Effect;" Vessel Shape, Total Vessel Volume, Opening Diameter, Percent Filled, Pouring Rate (fast or slow), whether the opening is occluded or not, and the nature (character) of the expulsion of ignited contents. This work, combined with some of the previous research conducted for litigation purposes, will be presented in this paper.

THE NECKED VESSEL FLAME THROWER EFFECT

This particular phenomenon is the expulsion of flaming vapor and liquid from a container filled with an ignitible liquid. The expulsion is the result of vapors within the container being ignited and an overpressure pressure event occurring as the contents of which are being poured onto or near a source of ignition. As the liquid is being poured, vapors surrounding the pour stream become ignited. The flame front then travels up the vapor trail and into the container, igniting the vapors within the container. The burning vapors become heated and expand, causing the pressure inside the container to rise. The higher pressure can cause gases, vapors and/or liquid within the container out through the opening of the container.

If the opening area of the vessel is significantly smaller the average cross section of the vessel, then the vessel may be referred to as a "necked vessel". If the burning vapors and liquids are expelled with sufficient volume and speed, the result is may be referred to as a "flame thrower". The combination of the conditions and the result were therefore named the "Necked Vessel Flame Thrower Effect".

While this name was coined over thirty-five years ago, new names have been applied whenever the phenomena "rediscovered" by other investigators. Recent names given to this same phenomena include "fire jet" and "flame jetting".

Although the Necked Vessel Flame Thrower Effect (NVFTE) is sometimes mischaracterized as an explosion, the reaction is seldom a true explosion as defined in National Fire Code NFPA 921 the *Guide for Fire and Explosion Investigations*[1] as there is rarely any damage or change to the containing vessel. Most frequently the nature of the combustion reaction is a flash fire.

> **NFPA 921-2014**
> **§3.3.53 Explosion. "**The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gases under pressure, or the release of gas under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials."
>
> **§3.3.81 Flash Fire. "**A fire that spreads by means of a flame front rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure."

The explosion of a vessel from the Necked Vessel Flame Thrower Effect does occasionally occur in the real world and has been encountered in some of Kennedy and Associates' litigation cases. To date, whether for litigation cases or the specific research testing series which is the main subject of this paper, none of the vessels in the used by JAK&A have exploded under laboratory test conditions.

A detailed description of how the NVFTE occurs is as follows:

Movement of the Flammable Vapors to an Ignition Source and Flame Front to the Vessel

1. A stream of ignitable liquid is poured from the vessel.
2. Either through evaporation or kinetic agitation, vapors separate from the liquid.
3. The vapor surrounds the liquid stream as it falls.
4. The vapors may fall on or near a competent ignition source.

5. The vapors ignite when they come in contact with a competent ignition source.
6. The flame front travels up the vapor stream to the opening of the vessel.

Movement of the Flame Front through the Container

7. If the vapor/air mixture in the headspace is properly within the flammable/explosive range, ignition of the headspace will occur.
8. When the flame front reaches the vessel, the flame front travels through ignitable zone of vapors (between the lower and upper flammable limits) into the vessel headspace.
9. Vapors above the surface (and within ambient flammable limits) become ignited and the expanding flame front travels forward and is expelled out the opening.

Expulsion of Vapor and Liquid from the Vessel

10. Pressure inside the vessel starts to rise as soon as the flame front enters the vessel due to heating and expansion of gases and vapors.
11. As the front travels through the vessel, pressure begins to build above the liquid.
12. Pressure at the open end of the vessel is lower because it can escape through the opening.
13. Pressure at the rear of the vessel continues to rise due to inertia of the fluid and resistance to flow.
14. The initially spherical pressure wave depresses the surface of the liquid creating wavelets.
15. Wavelets are entrained as moving gas pushes from the rear of the vessel toward the opening at the front.
16. Burning and unburned vapors and liquid droplets within the vessel are pushed towards the opening.
17. A combination of vapor and liquids exit the front of the vessel through the opening.

Flame Thrower

18. Upon exiting the vessel, burning and unburned vapors and liquids are mixed with fresh air, supplying additional oxygen to the mixture.
19. The actual flame thrower effect can occur as a ball or stream of fire with expulsion of burning vapor, atomized liquid mist, globules of liquid fuel, or some combination of these elements.
20. The relationships among the vessel geometry, volume, headspace, opening and neck size, and pouring rate will control whether a flame thrower effect takes place, and if so, the power and size (Class) of the reaction for any given fuel.

History

The first litigation involving an incident in which burning ignitable liquid was propelled out of a container was filed in Louisville, Kentucky by Attorney Edward H. Stopher of the prestigious law firm, Boehl, Stopher & Graves in the 1978. John A. Kenney and Associates, Fire and Explosion Analysis Experts, were hired by the law firm to investigate the incident.

A young man, working as a busboy in a downtown Louisville hotel, was serving individual plates of flaming deserts to guests at a banquet. At a serving table set up in the banquet room, a waiter was ladling the already ignited orange-flavored alcoholic beverage from a large bowl onto individual plates of desert. When the supply of burning sauce in the bowl diminished, the waiter began to pour additional liqueur into the large bowl directly from its bottle. The waiter was unaware that an imperceptivity small amount of burning liqueur remained in the bottom of the bowl. When the fresh supply of liqueur was added to the bowl, its vapors were ignited and the “Necked Vessel Flame Thrower Effect” occurred. Flaming liquid and vapor was ejected from the bottle and struck the busboy standing across the table directly opposite the waiter. The busboy’s white cotton tunic was ignited and the busboy was severely burned.

Original investigative research by experts of John A. Kennedy and Associates discovered that this repeatable occurrence was a result of the ignitable liquid being poured out of the container into an open bowl already containing a barely visible open flame. Burning vapor of the liquid stream transmitted the flame back into the bottle and ignited the vapor/air mixture in the headspace of the bottle. This resulted in a significant overpressure in the bottle which expelled burning vapor and liquid out the spout.

The case, ultimately called the "Orange Flambé Case" after the brand of orange liqueur being poured, was a seminal event for the study and understanding of the phenomenon, and was a precursor to many similar cases that followed involving low flash point ignitible liquids. These liquids have been as varied as alcoholic beverages, gasoline, charcoal lighter fluid, model race car fuels, and most recently alcohol based "bio-fuels" and gelled alcohol fuels such as used in decorative flame fire pots and ornamental artificial fire places.

The first full-scale testing of the occurrence conducted in reference to the "Orange Flambé Case", and resulted in a pioneering research paper submitted to the prestigious fire science publication, *Fire Technology* in that late 1970's. The paper was named *"Necked Vessel Flame Thrower Effect"* and it was the first use of the name and first work documenting the phenomenon.

Subsequently over the ensuing decades many serious injuries and even deaths have been attributed to this type of occurrence. In addition to the isolated incidents of various sorts, cases of NVFTE come in waves as new products are introduced by, and sold to, manufacturers and individuals who do not understand the phenomenon. John A. Kennedy and Associates have been hired to handle many similar to the "Orange Flambé Case", involving various containers and fuel.

Hand carried containers for gasoline, both plastic and metal, have regularly been the subject of litigation as the result of NVFTE events. Once the largest manufacturer of plastic fuel containers, the Blitz Corporation was driven into bankruptcy and finally out of business as a result of multiple lawsuits. Other manufacturers have made many numerous design changes, and the price of the average gas can has more than tripled as a result of litigation and insurance costs.

The 1980's and 1990's saw many cases involving charcoal lighter fluid. The CPSC exercised its power to recall at least one product, and the containers in which the flammable liquid was sold underwent major design changes.[2]

The years of approximately 2010 – 2013 brought on a rash of NVFTE incidents and cases with the introduction of alcohol (both liquid and gel) fueled decorative fire pots and fire places. Many of these fuels and products have since been the subject of recall by the CPSC.[3]

Other cases involved model engine nitro fuel (nitromethane/methanol mixture) used to restart a bon-fire, and other fuels in the forms of fire starters, tiki-torch fuel, stove fuel, and distilled alcoholic beverages, to name a few.

One of the more sensational cases investigated by JAK&A occurred in 2006 and involved the use of 151 proof rum used to create a decorative fire in a trough behind a bar as the female bartenders danced on the bar, just as it was portrayed in the film "*Coyote Ugly*". An attempt to refill the still burning trough ended in a severe injury to a bar patron. It is believed that the stunt is no longer performed at any of the company's locations.

Much has been made for and against the use of flame arresters to prevent NVFTE type incidents. While research is currently underway at JAK&A, this paper does not address this particular aspect of research, incidents and litigation.

During the ensuing 3 ½ decades hundreds of full-scale "Necked Vessel Flame Thrower Effect" tests performed. It became evident that the expulsion of the flaming vapor and liquid from the necked vessel only happens under a specific narrow set of circumstances and conditions. These circumstances and conditions include, but are not limited to:

1. A significant amount of ullage (or headspace) within the vessel to allow a vapor mixture within the flammable range to accumulate.
2. Generally (but not always) the amount of liquid in the vessel is less than half the volume of the vessel.
3. The act of pouring cannot continuously occlude the vessel opening thereby preventing the entrainment of air into the headspace and the expulsion of the ignited contents.
4. Generally the actual "Necked Vessel Flame Thrower Effect" only occurs once per pour because the available oxygen within the vessel is consumed in the first combustion event.

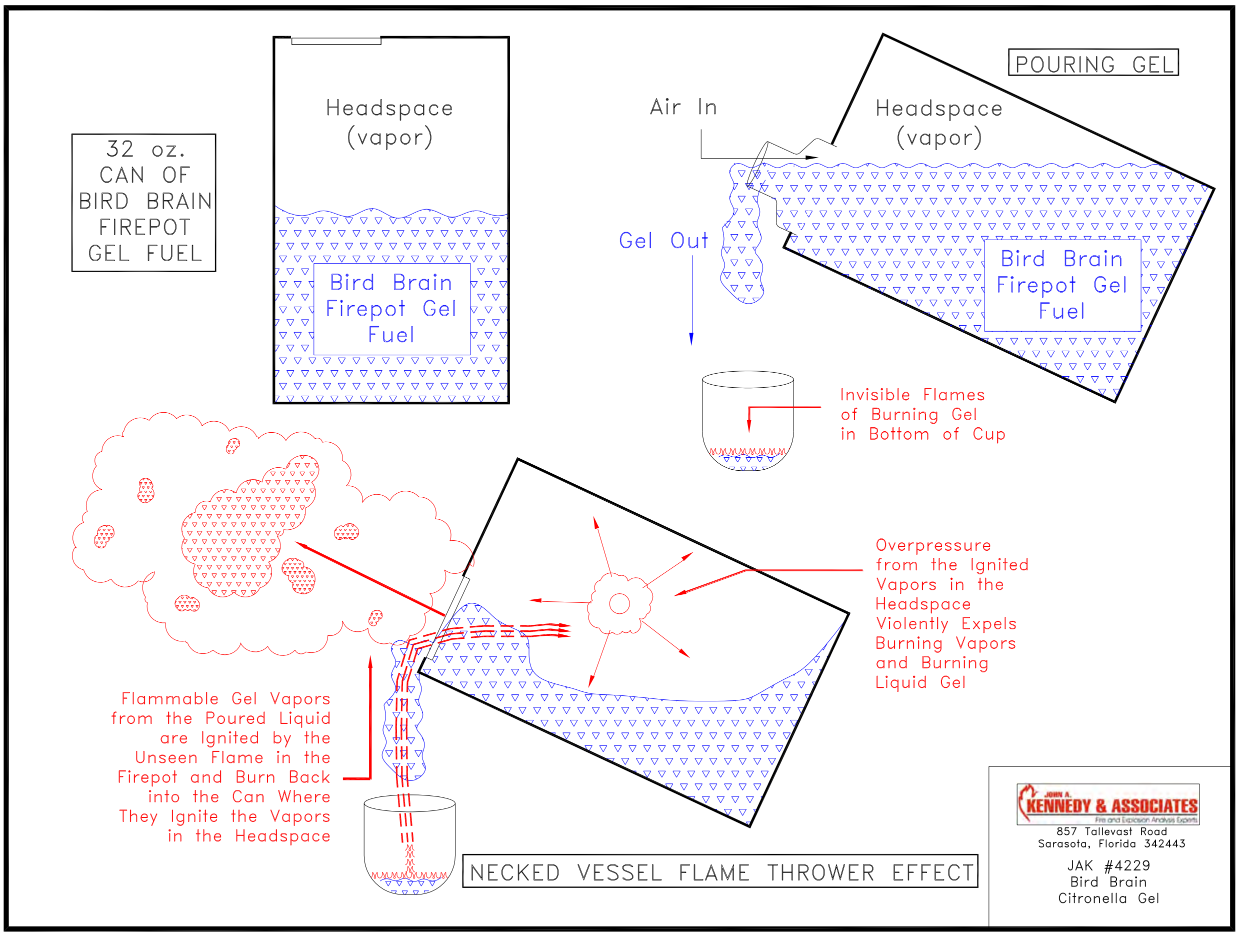


Figure 1. Illustration of the principle of the "Necked Vessel Flame Thrower Effect" from an actual litigation involving refill decorative fire pot gel fuel.

RESEARCH EXPERIMENTS

During the summer of 2013 the Forensic Fire Science and Technology Laboratories of John A. Kennedy and Associates undertook a major project of 82 tests to examine the variables in the Necked Vessel Fire Thrower Effect and how each measured variable affects the outcome. All tests were conducted with the same fuel under the same environmental conditions. What changed was the size and shape of the vessel, opening size, the amount of fill and pour rate. Combinations of these factors created addition factors considered in the analysis of the data.

All tests were fueled by Nu-Flame Liquid Bio-Ethanol Fuel. The properties of this fuel are: S.G. 0.797; Vapor Pressure @20C: 44.6 mm Hg; V.D.: 1.6; LEL: 3.3, UEL: 19.0; Flash Point: 58ºF. (14ºC) TCC; 70ºF (21ºC) TOC; Boiling Point: 173ºF (78ºC); Auto Ignition Temperature: 689 º F. (365 º C). [6,7].

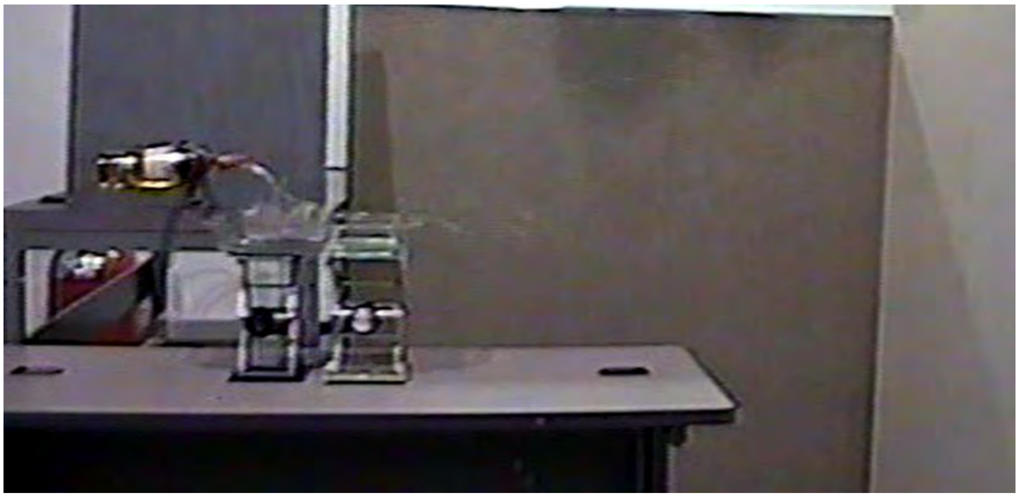


Figure 2. Still taken from a JAK&A video related to a case.
The incident being investigated occurred in 2006 and involved 151 proof rum.

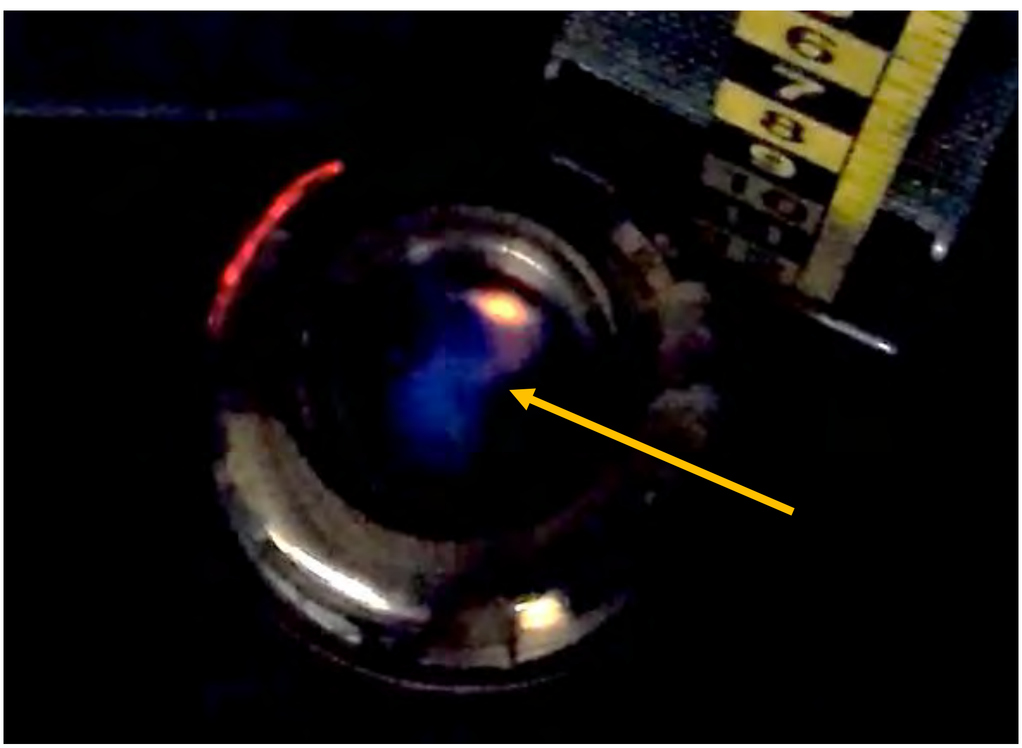


Figure 3. Still from a demonstration video made for an alcohol fuel gel case related to a 2011 incident.
The flame is barely perceptible in the bottom of a cup. A moment before, no flame was visible at all.

All vessel had openings that were centered in relation to the vessel's horizontal cross-section (i.e. spherical, conical or cylindrical shapes and radially symetrical).

All tests were performed on the same test jig. Each vessel was fastened into an adjustable cradle which could be rotated 360 degrees. A pilot flame of bio-ethanol in a petri dish is ignited and the vessel is rotated by hand from the rear of the apparatus, thereby pouring the contents of the vessel into the burning pilot flame. The ambient temperature in the laboratory for the tests was 78 º F. The entire testing process was captured on digital video.

Variables
In the testing, eight variables were evaluated for their effect on the nature of the flame thrower reaction.

- Eight different shaped vessels, mostly round in cross-section
- Vessel volume (50ml - 3875 ml)
- Vessel opening diameter (13.9 mm – 44.3 mm, 12.7 min with restrictor plate)
- Shape of the container
- Ratio of liquid to headspace (10% - 100%)
- Pour rate: Fast/Slow
- Occlusion of the vessel opening
- Nature (Class) of the flame thrower reaction

Individual variables examined
The test conducted for this study used a variety of glass and plastic vessels. Of the 82 tests conducted in this series 5 produced anomalous results because of human errors in pouring. These test results were removed from consideration in the overall analysis.

Vessel Volume
Generally speaking, the larger the volume of the container, the more likely the occurrence of a NVFTE event, and the higher volume discharged and velocity of the discharge.

Effects of Vessel Opening Diameter
The opening the vessel must be large enough to allow flame front to pass in without absorbing all of the heat. An opening too small can act as a flame arrester. The smallest opening of any vessel to be tested was 14 mm. The flame front was able to pass through this opening size. Further research will be conducted on this specific variable.

The ratio of the opening size relative to vessel volume also has a great effect. The smaller the ration of the cross sectional area to the total volume of the vessel, the higher the resulting velocity of the gases, vapors and liquid droplets being ejected from the vessel. As a general rule, the higher the ejection variety, the stronger the resultant NVFTE event.
In two tests, a restrictor plate of reduced diameter was attached to the vessel. As expected, the ejection velocity increased substantially.

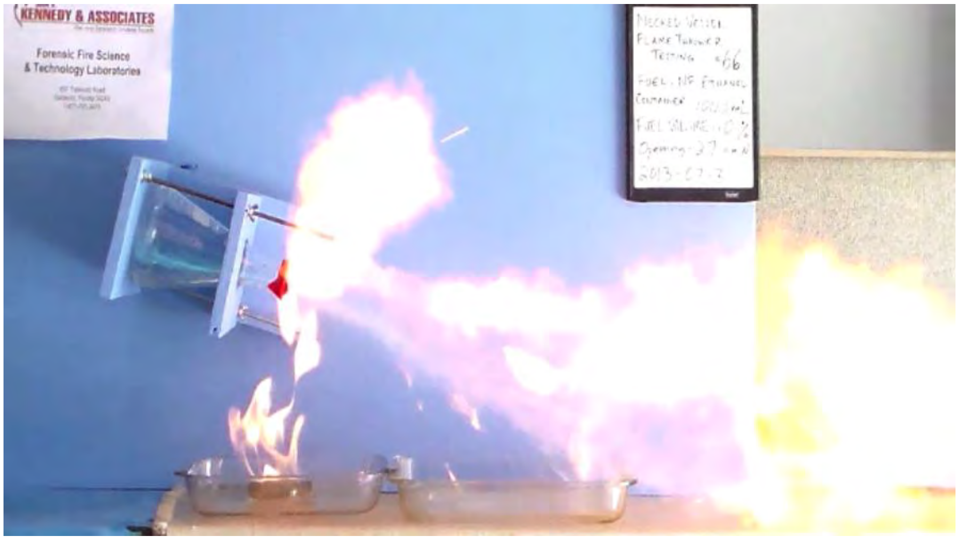


Figure 4. In Test 66, a steel restrictor plate was attached to the opening of the flask. The ejection velocity increased dramatically compared to the normal (larger) opening.

Effects of the Container Shape

When the shape of the vessel is such that there is little or no transition or "shoulder" between the body of the vessel and the neck (i.e. an Erlenmeyer flask or similar), the gases and vapors exiting the vessel may entrain less fuel in the form of liquid droplets, possibly the result of shallow liquid being pushed away from the opening. This may result in a weaker NVFTE.

Vessels with distinct transition, and deeper liquid depth near the opening (i.e. 2 liter beverage bottle or similar), may be encourage the formation of wavelets and droplet being entrained in outflow, and result in a stronger NVFTE.

More research will be conducted into this area of investigation.

Proportion of Headspace Volume to Fuel Volume

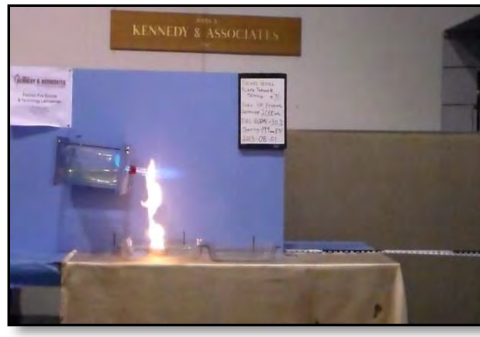
To a great extent, the volume of the headspace is proportional to the velocity of the gases and vapors exiting the vessel, and therefore to the velocity of the NVFTE event. This changes, however, when the volume of fuel become very low when compared to the headspace. As the volume of the fuel in the vessel approaches zero, not enough fuel exists to be ejected from the vessel and eventually to even fuel the initial pressure event itself.

Conversely, as head space decreases, the about of fuel vapors and available oxygen also decrease. A point will be reached where there an insufficient amount of fuel vapors and oxygen to create sufficient pressure to cause the vessels contents to be expelled, and an NVFTE event will not occur.

Occlusion of the Vessel Opening

Occlusion of the vessel opening refers to the covering of the opening by the liquid fuel during the poring process. This generally occurs when the amount of liquid in the vessel is 50% or more of the total vessel volume, and the rate of pouring is sufficiently fast to cause the occlusion. Occlusion effectively prevents the flame burning up the vapors emitting from the stream of pouring liquid from entering the vessel and igniting the headspace.

a) Stream of liquid and vapor spill down.



b) Flame front travel up the stream.

c) Fluid beginsejection as flame enters vessel.

d) Pressure increases as flame front progresses.

e) Vessel approaches max. pressure.

f) Flame extinguished inside vessel.

g) Expelled fluid separate from vessel.

h) Fluid continues to pour after NVFTE.

Figure 5. Representative still photos from digital video of Test 78.
2000 ml Plastic Water Bottle with 3" extended neck, 19.9 mm opening, 30% filled, slow pour rate, opening not occluded.
This produced a Class 4 reaction.

Effects of Pouring Speed
The speed at which the vessel is turned to pour affects both whether an NVFTE event occurs, and the type of event that results.

An extremely slow pour may diminish the amount of liquid droplets ejected and result in a weak NVFTE event may occur.

A pour of “moderate” speed may render the strongest NVFTE event in terms of ejection velocity of and flame travel distance. This could be described as a “fire stream”. This would indicate laminar flow out of the vessel.

A fast pour may intermittently or fully occlude the opening of the vessel. A fully occluded opening would prevent the NVFTE event altogether. An intermittently occluded opening may pass the flame front into the vessel. A possible outcome is a high volume of fully liquid fuel ejected under a higher pressure. This could be described as a “fire ball”. This would indicate a very turbulent flow out of the vessel.

Nature (Class) of the Flame Thrower Reaction
The reactions of each of the 82 tests were characterized in five classes.

> **Class 0 -** No combustion reaction within the test vessel
>
> **Class 1 –** A small visible combustion flame within the test vessel without any significant extension of vapor only flame out of the vessel neck.
>
> **Class 2 –** Vapor ignition and some atomized liquid fueled expulsion from within the test vessel without significant ejection of burning liquid.
>
> **Class 3 –** Significant flame thrower effect with burning vapor cloud, readily identifiable atomized liquid and significant ejection of burning liquid up to five feet in linear distance from the vessel opening.
>
> **Class 4 -** Substantial flame thrower effect with burning vapor cloud, large atomized liquid fireball and significant ejection of burning liquid over five feet in linear distance from the vessel opening.

Discounting the 5 anomalous tests, of the remaining 77 tests:

- 19 tests were classified as Class 0.
- 21 tests were classified as Class 1.
- 7 tests were classified as Class 2.
- 10 tests were classified as Class 3.
- 20 tests produced Class 4 results.

The results were 25% of the tests produced no NVFTE event at all. 36% of the events resulted in weak NVFTE events (Class 1 or Class 2). The remaining 39% resulted in a strong NVFTE event (Class 3 or Class 4).

TEST	VESSEL SHAPE	TOTAL VOLUME	OPENING DIAMETER	% FILLED	POUR RATE	OCCLUDED OPENING	NATURE OF EXPULSION	REMARKS
1	Erlenmeyer	50 ml	15.1 mm	10	SLOW	NO	-----	
2	Erlenmeyer	50 ml	15.1 mm	20	SLOW	No	-----	
3	Erlenmeyer	50 ml	15.1 mm	50	SLOW	No	+	
4	Erlenmeyer	250 ml	28.1 mm	10	SLOW	No	+	
5	Erlenmeyer	250 ml	28.1 mm	25	SLOW	No	+	
6	Erlenmeyer	250 ml	28.1 mm	50	SLOW	No	+	
7	Erlenmeyer	500 ml	32.4 mm	10	SLOW	No	+	
8	Erlenmeyer	500 ml	32.4 mm	25	SLOW	No	+	
9	Erlenmeyer	500 ml	32.4 mm	50	SLOW	No	+	
10	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	++	
11	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	++	
12	Erlenmeyer	1000 ml	39.1 mm	50	SLOW	No	++	
13	Erlenmeyer	2000 ml	44.3 mm	10	SLOW	No	+	
14	Erlenmeyer	2000 ml	44.3 mm	25	SLOW	No	+	
15	Erlenmeyer	2000 ml	44.3 mm	50	SLOW	No	+	
16	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	++	2 min. wait
17	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	++	4 min. wait
18	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	++	8 min. wait
19	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	++	16 min. wait
20	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	+++++	
21	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	+	Anomalous
22	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	++++	
23	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	++++	Close up
24	Bottle	500 ml	38.0 mm	20	SLOW	No	+	Flicker
25	Bottle	500 ml	38.0 mm	20	SLOW	No	+	Flicker
26	Bottle	500 ml	38.0 mm	20	SLOW	No	+	Flicker
27	Boiling flask	250 ml	24.6 mm	25	SLOW	No	+	3 in. neck
28	Boiling flask	250 ml	24.6 mm	25	SLOW	No	+	3 in. neck
29	Boiling flask	250 ml	24.6 mm	25	SLOW	No	+	3 in. neck
30	Boiling flask	500 ml	28.3 mm	25	SLOW	No	+	5 in. neck
31	Boiling flask	500 ml	28.3 mm	25	SLOW	No	+	5 in. neck
32	Boiling flask	500 ml	28.3 mm	25	SLOW	No	----	5 in. neck
33	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	++++	3 in. neck
34	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	-----	Anomalous
35	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	++++	Anomalous
36	Aluminum can	710 ml	29 mm	10	SLOW	No	+++	
37	Aluminum can	710 ml	29 mm	10	SLOW	No	+++	
38	Aluminum can	710 ml	29 mm	25	SLOW	No	+++	
39	1 gal. milk jug	3785 ml	30 mm	5	SLOW	No	++++	
40	Boiling flask	250 ml	24.6 mm	50	FAST	No	+++	
41	Boiling flask	250 ml	24.6 mm	70	FAST	No	++++	
42	Boiling flask	250 ml	24.6 mm	100	FAST	Yes	++++	
43	Boiling flask	500 ml	27.3 mm	50	FAST	No	++++	
44	Boiling flask	500 ml	27.3 mm	50	FAST	Yes/No	++++	
45	Boiling flask	500 ml	27.3 mm	70	FAST	No	++++	
46	Boiling flask	500 ml	27.3 mm	100	FAST	No	++++	
47	Plastic bottle	355 ml	21.4 mm	20	SLOW	No	+++	
48	Plastic bottle	355 ml	21.4 mm	50	FAST	No	++++	
49	Plastic bottle	355 ml	21.4 mm	70	FAST	No	+++	
50	Plastic bottle	355 ml	21.4 mm	70	FAST	Yes	----	
51	Plastic bottle	355 ml	21.4 mm	70	FAST	Yes	----	
52	Plastic bottle	355 ml	21.4 mm	100	FAST	Yes	----	
53	Plastic bottle	355 ml	21.4 mm	100	FAST	Yes	----	
54	Tall plastic bottle	700 ml	21.6 mm	20	FAST	Yes	----	
55	Tall plastic bottle	700 ml	21.6 mm	50	FAST	Yes	----	

Table 1. Raw Data from the 2013 Testing Series.
(Continued on next page.)

TEST	VESSEL SHAPE	TOTAL VOLUME	OPENING DIAMETER	% FILLED	POUR RATE	OCCLUDED OPENING	NATURE OF EXPULSION	REMARKS
56	Tall plastic bottle	700 ml	21.6 mm	70	FAST	Yes	----	
57	Tall plastic bottle	700 ml	21.6 mm	100	SLOW	No	++	Anomalous
58	Tall plastic bottle	700 ml	21.6 mm	100	FAST	Yes	----	Re-do of #57
59	Tall plastic bottle	1000 ml	21.7 mm	20	FAST	Yes/No	---- ++	
60	Tall plastic bottle	1000 ml	21.5 mm	50	FAST	Yes	----	
61	Tall plastic bottle	1000 ml	21.5 mm	70	FAST	Yes	----	
62	Tall plastic bottle	1000 ml	21.5 mm	100	FAST	Yes	----	
63	Plastic bottle	355 ml	21.5 mm	45	SLOW	No	+	
64	Plastic bottle	355 ml	21.5 mm	45	SLOW	No	+	
65	Erlenmeyer flask	1000 ml	17.6 mm	10	SLOW	No	++++	Restrictor
66	Erlenmeyer flask	1000 ml	12.7 mm	10	SLOW	No	++++	Restrictor
67	Plastic bottle	355 ml	21.5 mm	30	SLOW	No	+	
68	Plastic bottle	355 ml	21.5 mm	30	FAST	No	+++	
69	Plastic bottle	355 ml	19.9 mm	30	SLOW	No	+++	Extended neck Anomalous
70	Plastic bottle	355 ml	19.9 mm	30	FAST	No	++++	Extended neck
71	Plastic bottle	355 ml	19.9 mm	30	FAST	Yes	++++	Extended neck
72	Plastic bottle	1000 ml	19.9 mm	30	SLOW	No	++++	Extended neck
73	Plastic bottle	1000 ml	19.9 mm	30	SLOW	No	++++	Extended neck
74	Plastic bottle	1000 ml	19.9 mm	30	FAST	Yes	----	Extended neck
75	Tall plastic bottle	1000 ml	21.5 mm	30	SLOW	No	+++	
76	Tall plastic bottle	1000 ml	21.5 mm	30	SLOW	No	+++	
77	Tall plastic bottle	1000 ml	21.5 mm	30	FAST	Yes	-----	
78	Plastic bottle	2000 ml	19.9 mm	30	SLOW	No	++++	Extended neck
79	Plastic bottle	2000 ml	19.9 mm	30	FAST	Yes	----	Extended neck
80	Plastic bottle	2000 ml	19.9 mm	30	FAST	Yes	----	Extended neck
81	Plastic bottle	2000 ml	21.5 mm	30	SLOW	No	+++	
82	Plastic bottle	2000 ml	21.5 mm	30	SLOW	No	++++	

Table 1. Raw Data from the 2013 Testing Series.
(Continued from previous page.)

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No Event	**Class 1**	**Class 2**	**Class 3**	**Class 4**

Table 2. Legend for "Nature of Expulsion"

Other Research

Other research has been conducted into the Necked Vessel Flame Thrower Effect. Little research has been found which goes beyond replication or proof of known incidents. That which does tends to focus on the concentration of vapor inside of gasoline containers, or if gasoline containers can actually rupture and explode. We believe this is the first research which attempts to understand the phenomenon in full detail. Following is a chronological listing of related research found:

NBS Technical Note 850, “Gasoline and Gasoline Container Fire Incidents,” E. Tyrell, 1975. NBS. *(now NIST)*

"Case study: Flame Arresters and Exploding Gasoline Containers", L.C. Hasselbring, 2006. Journal of Hazardous Materials.

U.S. Department of Justice Laboratory Report, "Majd Al-Shara Fire", A. St. John, December 2010. The Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory.

“Failure Analysis and Prevention of Fires and Explosions with Plastic Gasoline Containers”, G. Stevick, J. Zicherman, D. Rondinone, A. Sagle. Published online: 4 May 2011, ASM International.

“Hazard Assessment of Portable Gasoline Container Flammability", B.E. Elias, 2011. Master Thesis, Worcester Polytechnical Institute.

“Portable Plastic Gasoline Container Explosions and Their Prevention”, G. Stevick, D. Rondinone, A. Sagle, 2011, Journal of Failure Analysis and Prevention

NIST Technical Note 1791, “Evaluation of Firepots and Gel Fuels”, N.D. Marsh, March 2013. Fire Research Division, Engineering Laboratory, NIST. *Testing done in conjunction with the U.S. Consumer Product Safety Commission.*

SUMMARY OF PRELIMINARY CONCLUSIONS

It is clear that more analysis remains to be done. We can, however, still come to certain significant early conclusions from our 35 years of experience with investigation, research and litigation cases.

First, it should be noted that while all of the research project tests were conducted with a single fuel, the principles can be applied to any ignitible liquid fuel when the temperature of the fuel is above its flashpoint.

Second, we can develop some general rules for determining the likelihood of a Necked Vessel Flame Thrower Effect incident occurring.

Conditions Favorable the Flame Thrower effect

1. The ambient temperature being above the flashpoint of the liquid fuel.
2. The vessel must have a spout opening large enough to allow the passage of a flame front through its entire length with enough residual energy to ignite the fuel vapor/air mixture it encounters when entering the headspace in the vessel.
3. The vessel must have a spout opening with a cross sectional area small enough when compared to the volume of the vessel to allow for adequate build-up of pressure within the vessel to expel vapors and/or liquids.
4. Sufficient headspace within the vessel when the flame front arrives to support adequate combustion to generate sufficient pressure to expel vapors and/or liquids.
5. Sufficient ignitible liquid vapor within the vessel to support adequate combustion to generate sufficient pressure to expel vapor and liquids, as well as the vapors and liquids to be expelled.

Conditions Unfavorable the Flame Thrower effect

1. The ambient temperature being below the flashpoint of the liquid fuel.
2. If the opening is too large relative to the volume, the pressure generated will be insufficient to eject vapors and/or liquids from the vessel.
3. If the opening is too small or if the vessel’s neck is too long, the heat energy of the flame front will be transferred to the liquid surface and the interior of the neck thereby quenching the flame, much as the action of a flame arrester.

4. If the opening may be occluded by the liquid, the flame cannot pass through the liquid and no further reaction will occur.
5. If the vapor/air mixture in the headspace is above or below the flammable/explosive range, ignition of the vapors in the headspace will not occur.
6. Vessels that are completely or nearly full may have insufficient headspace to support enough combustion to provide sufficient pressure to eject vapors and/or liquids.
7. Vessels that are nearly empty may have insufficient fuel to support enough combustion to provide sufficient pressure to eject vapors and/or liquids, and not enough vapors and liquid to be expelled.

Lastly, Necked Vessel Flame Thrower Effect events happen far more often than what is reported to or investigated by fire professionals. The vast majority of incidents never come to the attention of the public sector, private sector, or the courts. Our independent research shows that as much as 61% of all potential Necked Vessel Flame Thrower Effect incidents are of Class 0, 1 or 2 and do not produce significant fire danger. Of the remaining 39% of such incidents, few come to the attention of the public or private sector as they do not produce "reportable" damage or injuries. It is only those incidents which cause significant property damage, a serious injury or a death that make their way to the evening news, and on to the attention of fire investigators, fire analysts and fire protection specialists, or the courtroom.

The use of flame arrester type devices to prevent Necked Vessel Flame Thrower Effect type incidents requires further inquiry, and research is currently under way.

ABOUT THE AUTHORS

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ENDNOTES

[1] NFPA 921-2014 Guide for Fire and Explosion Investigations, National Fire Protection Association, Quincy, MA (2014)
[2] U.S. Consumer Product Safety Commission recall #91-061, April 24, 1991. Lantec, Inc. Recalls Eco-Lite Charcoal Starter.
[3] U.S. Consumer Products Safety Commission press release #11-315, September 15, 2011. "Nine Manufacturers, Distributors Announce Consumer Recall of Portable Gel Fuels Due to Burn and Flash Fire Hazards"
[4] Nu-Flame Liquid Bio-Ethanol MSDS, 01/20/12, Bluworld HOMElements LLC, Orlando, FL
[5] Kennedy, Patrick and Kennedy, John, Explosion Investigation and Analysis – Kennedy on Explosions, Investigations Institute, Chicago, 1990