A DETAILED LOOK AT THE NECKED VESSEL FLAME THROWER EFFECT

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ABSTRACT

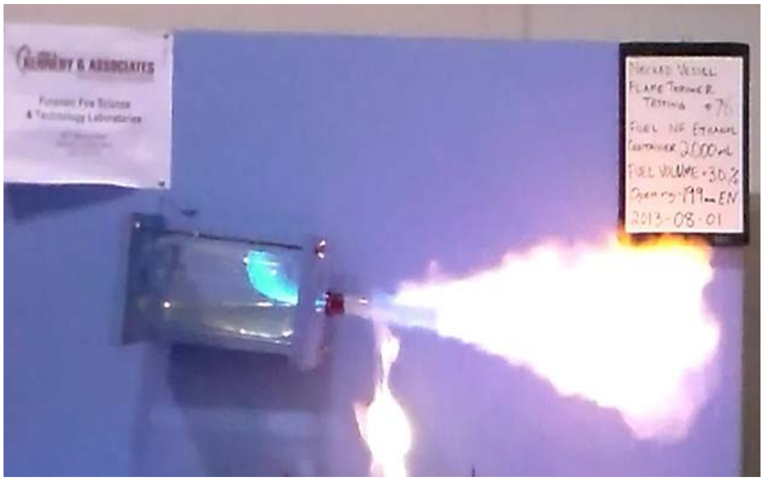


Figure 1. Necked Vessel Flame Thrower Effect test at JAK&A Laboratories.

Fire and explosion incidents involving ignitable liquids carried in and poured from containers have likely occurred for as 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 has lately become a "cause célèbre" and the frequent subject of litigation. This particular phenomenon is the overpressure and expulsion of flaming vapor and liquid from a container the when the contents are being poured near or onto 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.

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 several variables and their interactions. It is these variables and the results of 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. 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 and 2014 extensive study and laboratory tests were conducted outside the scope of any specific incident or litigation. This data was combined with data collected during case specific research conducted during the previous 36 years. The study viewed and evaluated the variables in producing the "Necked Vessel Flame Thrower Effect", including: Vessel Shape, Total Vessel Volume, Opening Diameter, Percent Filled, Pouring Rate (fast or slow), Fuel Temperature and Flashpoint, 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 defined as the expulsion of flaming vapor and liquid from a container filled with an ignitable liquid. This 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. This rise in pressure can force gases, vapors and/or liquid within the container out through its opening.

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, but only in rare 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.

HISTORY

The first well documented case of NVFTE was investigated by John A. Kennedy & Associates in preparation for litigation related to the incident. The case was filed in Louisville, Kentucky by Attorney Edward H. Stopher of the law firm Boehl, Stopher & Graves in the 1978. The incident involved which burning ignitable liquid was propelled out of a container at a downtown Louisville hotel restaurant.

A busboy was serving plates of a flambé desert to guests at a banquet. At a nearby serving table, a waiter was ladling burning orange-flavored alcoholic beverage from a large bowl onto each desert plate. The level of burning sauce in the bowl became low. Believing the flames to be extinguished, the waiter began to pour additional liqueur into the bowl directly from a bottle, unaware that a minute flame remained at the bottom of the bowl. When more liqueur was added to the bowl, its vapors were ignited and the "Necked Vessel Flame Thrower Effect" occurred. Flaming vapor and liquid droplets were ejected from the bottle and struck the busboy standing directly across the table from the waiter. The busboy's white cotton tunic was ignited and the he was severely burned.

Upon investigation, it was discovered that this was a repeatable phenomenon and the result of the ignitable liquid being poured out of the necked vessel into an open bowl 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.

The case became known as the "Orange Flambé Case" after the brand of orange liqueur being poured. It 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 range from petroleum based fuels to alcoholic beverages.

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 1979. 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 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. Other NVFTE incidents specifically investigated by John A. Kennedy and Associates include:

- Tiki-torch fuels and refill containers.
- Liquid stove fuels and refill containers.
- Distilled alcoholic beverages and containers.
- Model engine nitro fuel (nitromethane/methanol mixture) improperly used to restart a bon-fire.
- Charcoal lighter fluid and containers. Many cases occurred in the 1980's and 1990's, and the CPSC exercised its power to recall at least one product. Major design changes were made to the containers in which the flammable liquid was sold.[2]
- Hand carried gasoline containers. These are regular subjects of litigation as the result of NVFTE events. The Blitz Corporation, once the largest manufacturer of plastic fuel containers, was driven into bankruptcy and eventually 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 in the last two decades as a result of litigation and insurance costs.[3]
- Liquid and gelled alcohol fuels and containers. The years of 2010 – 2014 brought on a rash of NVFTE incidents and cases with the introduction of alcohol fueled decorative fire pots and fire places. Many of these fuels, containers and burner products have since been the subject of recall by the CPSC.[4]

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 last 36 years hundreds of full-scale "Necked Vessel Flame Thrower Effect" tests performed at JAK&A. 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. The liquid must be above its flash point.
2. A significant amount of ullage (or headspace) must exist (either before or during the pouring process) within the vessel to allow a vapor mixture within the flammable range to accumulate.
3. Generally (but not always) the amount of liquid in the vessel is less than half the volume of the vessel.
4. 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.
5. Generally the actual NVFTE event occurs only once per pour because the available oxygen within the vessel is consumed in the first combustion event.

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

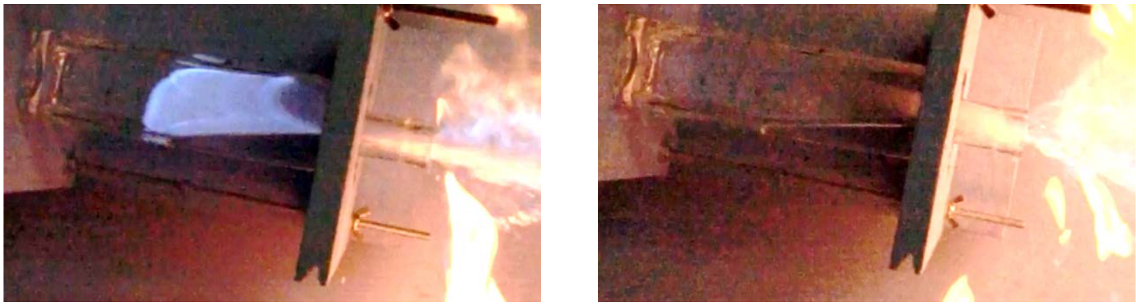
7. If a portion of the vapor/air mixture in the headspace is properly within the flammable/ explosive range, ignition of the headspace will occur.
8. When the flame front reaches the vessel, the flame front travels through ignitable zone of vapors (between the lower and upper flammable limits) into the 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 pressure wave depresses the surface of the liquid, accelerating its flow towards the opening.
15. Vapor flows rapidly across the surface of the liquid through the narrower opening of the vessel.
16. The liquid separates into droplets as it reaches the vessels opening.
17. A combination of vapor and liquid droplets exit the front of the vessel through the opening.

a) Flame front entering neck of vessel.

b) Flame front propagating across liquid surface. Liquid begins to eject from vessel.



c) Flame front spreading through flammable vapor. Liquid transitions to droplets as velocity increases.

d) Combustion ceases inside vessel, but droplets continue to be ejected.

e) Negative pressure wave begins to enter vessel, dragging a small flame front with it.

d) Negative pressure creates large waves in liquid, oxygen is inadequate for sustained combustion.

Figure 2. A series of still photos from digital high speed video.
500 ml square glass bottle, 16.4 mm ID opening x 50 mm neck,
20% filled, slow pour rate, opening not occluded.

Flame Thrower

18. Upon exiting the vessel, burning and unburned vapors and liquid droplets begin mixing with fresh air, supplying additional oxygen to the air/fuel mixture.
19. The droplets continue to vaporize as they travel through the air.
20. The flame enlarges as additional vapors are emitted and ignited.

Flame Shape

- The actual flame thrower effect can occur as an expulsion of burning vapor, atomized liquid mist, globules of liquid fuel, or some combination of these elements. The event can appear as either a round “ball” of fire, a long “stream” of fire, or a combination of the two.
- 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.

RESEARCH EXPERIMENTS

Between 1978 and 2013 research was done in relation to various specific incidents and related litigation. Some of this research was used for this paper.

Figure 3. Still taken from a JAK&A video related to a case.
The incident being investigated occurred in 2006 and involved 151 proof rum.

Figure 4. 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. Moments before and after, no flame was visible at all.

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 of these 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 of the 2013 tests used 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: 14^{o}C (58^{o}F) TCC; 21^{o}C (70^{o}F) TOC; Boiling Point: 78^{o}C (173^{o}F); Auto Ignition Temperature: 365^o C (689^{o}F). [5,6]

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 symmetrical).

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 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, seven 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

RESULTS

Nature (Class) of the Flame Thrower Reaction

The reactions of each of the tests were characterized into one of 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 (1.52 m) 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 (3.05 m) in linear distance from the vessel opening.

The results of 5 tests were determined to be anomalous. Discounting these, 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 were classified as **Class 4**.

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	0	
2	Erlenmeyer	50 ml	15.1 mm	20	SLOW	No	0	
3	Erlenmeyer	50 ml	15.1 mm	50	SLOW	No	1	
4	Erlenmeyer	250 ml	28.1 mm	10	SLOW	No	1	
5	Erlenmeyer	250 ml	28.1 mm	25	SLOW	No	1	
6	Erlenmeyer	250 ml	28.1 mm	50	SLOW	No	1	
7	Erlenmeyer	500 ml	32.4 mm	10	SLOW	No	1	
8	Erlenmeyer	500 ml	32.4 mm	25	SLOW	No	1	
9	Erlenmeyer	500 ml	32.4 mm	50	SLOW	No	1	
10	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	2	
11	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	2	
12	Erlenmeyer	1000 ml	39.1 mm	50	SLOW	No	2	
13	Erlenmeyer	2000 ml	44.3 mm	10	SLOW	No	1	
14	Erlenmeyer	2000 ml	44.3 mm	25	SLOW	No	1	
15	Erlenmeyer	2000 ml	44.3 mm	50	SLOW	No	1	
16	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	2	2 min. wait
17	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	2	4 min. wait
18	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	2	8 min. wait
19	Erlenmeyer	1000 ml	39.1 mm	10	SLOW	No	2	16 min. wait
20	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	4+	
21	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	1	Anomalous
22	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	4	
23	Erlenmeyer	1000 ml	39.1 mm	25	SLOW	No	4	Close up
24	Bottle	500 ml	38.0 mm	20	SLOW	No	1	Flicker
25	Bottle	500 ml	38.0 mm	20	SLOW	No	1	Flicker
26	Bottle	500 ml	38.0 mm	20	SLOW	No	1	Flicker
27	Boiling flask	250 ml	24.6 mm	25	SLOW	No	1	3 in. neck
28	Boiling flask	250 ml	24.6 mm	25	SLOW	No	1	3 in. neck
29	Boiling flask	250 ml	24.6 mm	25	SLOW	No	1	3 in. neck
30	Boiling flask	500 ml	28.3 mm	25	SLOW	No	1	5 in. neck
31	Boiling flask	500 ml	28.3 mm	25	SLOW	No	1	5 in. neck
32	Boiling flask	500 ml	28.3 mm	25	SLOW	No	0	5 in. neck
33	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	4	3 in. neck
34	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	0	Anomalous
35	Liquor bottle	1750 ml	25.3 mm	10	SLOW	No	4	Anomalous
36	Aluminum can	710 ml	29 mm	10	SLOW	No	3	
37	Aluminum can	710 ml	29 mm	10	SLOW	No	3	
38	Aluminum can	710 ml	29 mm	25	SLOW	No	3	
39	1 gal. milk jug	3785 ml	30 mm	5	SLOW	No	4	
40	Boiling flask	250 ml	24.6 mm	50	FAST	No	3	
41	Boiling flask	250 ml	24.6 mm	70	FAST	No	4	
42	Boiling flask	250 ml	24.6 mm	100	FAST	Yes	4	
43	Boiling flask	500 ml	27.3 mm	50	FAST	No	4	
44	Boiling flask	500 ml	27.3 mm	50	FAST	Yes/No	4	
45	Boiling flask	500 ml	27.3 mm	70	FAST	No	4	
46	Boiling flask	500 ml	27.3 mm	100	FAST	No	4	

Table 2. 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
47	Plastic bottle	355 ml	21.4 mm	20	SLOW	No	3	
48	Plastic bottle	355 ml	21.4 mm	50	FAST	No	4	
49	Plastic bottle	355 ml	21.4 mm	70	FAST	No	3	
50	Plastic bottle	355 ml	21.4 mm	70	FAST	Yes	0	
51	Plastic bottle	355 ml	21.4 mm	70	FAST	Yes	0	
52	Plastic bottle	355 ml	21.4 mm	100	FAST	Yes	0	
53	Plastic bottle	355 ml	21.4 mm	100	FAST	Yes	0	
54	Tall plastic bottle	700 ml	21.6 mm	20	FAST	Yes	0	
55	Tall plastic bottle	700 ml	21.6 mm	50	FAST	Yes	0	
56	Tall plastic bottle	700 ml	21.6 mm	70	FAST	Yes	0	
57	Tall plastic bottle	700 ml	21.6 mm	100	SLOW	No	2	Anomalous
58	Tall plastic bottle	700 ml	21.6 mm	100	FAST	Yes	0	Re-do of #57
59	Tall plastic bottle	1000 ml	21.7 mm	20	FAST	Yes/No	0 / 2	
60	Tall plastic bottle	1000 ml	21.5 mm	50	FAST	Yes	0	
61	Tall plastic bottle	1000 ml	21.5 mm	70	FAST	Yes	0	
62	Tall plastic bottle	1000 ml	21.5 mm	100	FAST	Yes	0	
63	Plastic bottle	355 ml	21.5 mm	45	SLOW	No	1	
64	Plastic bottle	355 ml	21.5 mm	45	SLOW	No	1	
65	Erlenmeyer flask	1000 ml	17.6 mm	10	SLOW	No	4	Restrictor
66	Erlenmeyer flask	1000 ml	12.7 mm	10	SLOW	No	4	Restrictor
67	Plastic bottle	355 ml	21.5 mm	30	SLOW	No	1	
68	Plastic bottle	355 ml	21.5 mm	30	FAST	No	3	
69	Plastic bottle	355 ml	19.9 mm	30	SLOW	No	3	Extended neck Anomalous
70	Plastic bottle	355 ml	19.9 mm	30	FAST	No	4	Extended neck
71	Plastic bottle	355 ml	19.9 mm	30	FAST	Yes	4	Extended neck
72	Plastic bottle	1000 ml	19.9 mm	30	SLOW	No	4	Extended neck
73	Plastic bottle	1000 ml	19.9 mm	30	SLOW	No	4	Extended neck
74	Plastic bottle	1000 ml	19.9 mm	30	FAST	Yes	0	Extended neck
75	Tall plastic bottle	1000 ml	21.5 mm	30	SLOW	No	3	
76	Tall plastic bottle	1000 ml	21.5 mm	30	SLOW	No	3	
77	Tall plastic bottle	1000 ml	21.5 mm	30	FAST	Yes	0	
78	Plastic bottle	2000 ml	19.9 mm	30	SLOW	No	4	Extended neck
79	Plastic bottle	2000 ml	19.9 mm	30	FAST	Yes	0	Extended neck
80	Plastic bottle	2000 ml	19.9 mm	30	FAST	Yes	0	Extended neck
81	Plastic bottle	2000 ml	21.5 mm	30	SLOW	No	3	
82	Plastic bottle	2000 ml	21.5 mm	30	SLOW	No	4	

Table 1. Raw Data from the 2013 Testing Series.

(Continued from previous page.)

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, the higher volume of vapors and liquid ejected, and the higher velocity of the ejected fluids.

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 ratio of the cross sectional area of the opening to the total volume of the vessel, the higher the resulting velocity of the ejection. As a general rule, the higher the ejection velocity, 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.

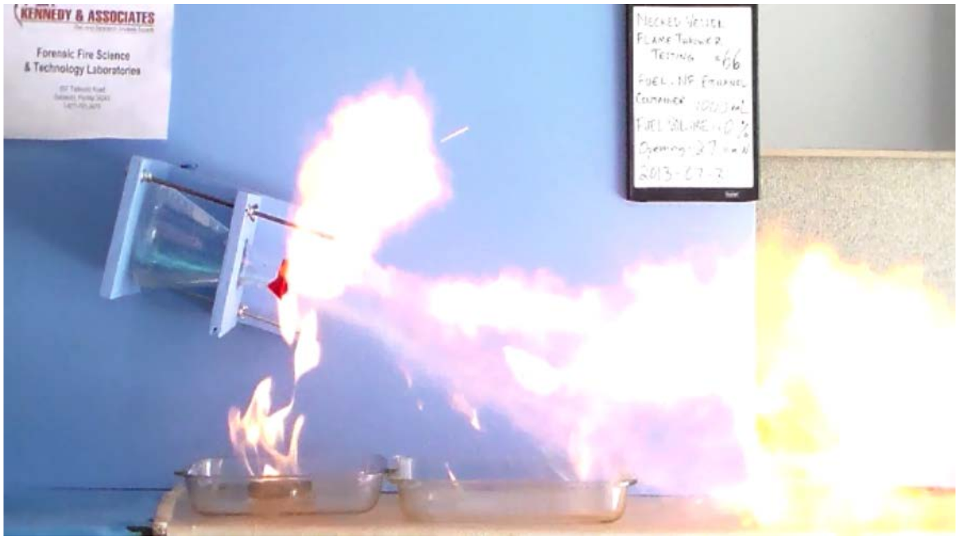


Figure 5. In Test 66, a steel restrictor washer was attached to the opening of the flask, reducing the opening area by 80%. The ejection velocity increased dramatically compared to the normal (larger) opening.

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.

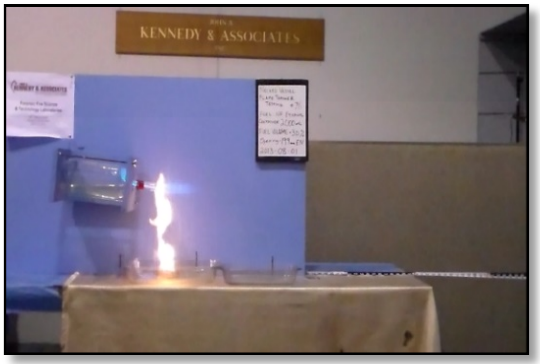
Vessels with distinct transition, and deeper liquid depth near the opening (i.e. 2 liter beverage bottle or similar), may encourage the formation of wavelets and droplets being entrained in outflow, and result in a stronger NVFTE.

More research will be conducted into this area of investigation.

Proportion of Headspace Volume to Fuel Volume

The NVFTE event is dependent on the amount of fuel within the vessel. If there is too much fuel (and too little headspace), there will be insufficient combustion and not enough pressure will be generated to cause a significant ejection of liquid or droplets. The result will be either a weak NVFTE event, or no event at all. If, on the other hand, there is too little fuel in the vessel, there may be little or no fuel left to be expelled after combustion takes place.

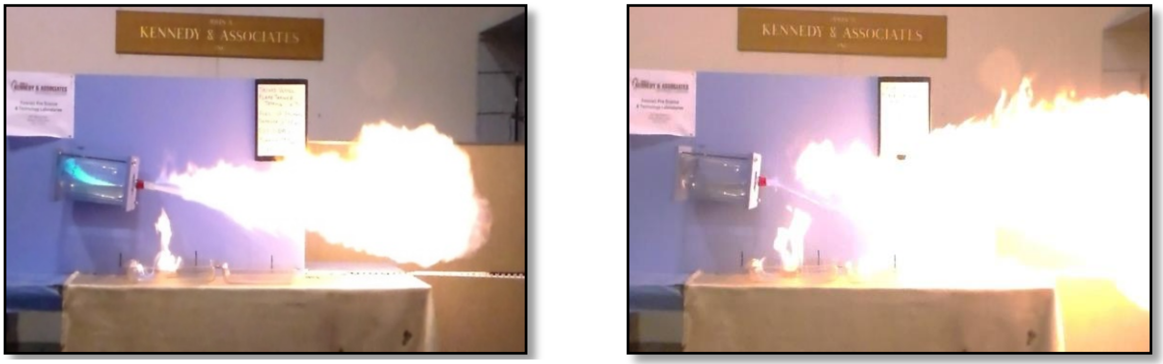
a) Stream of liquid and vapor spill down.



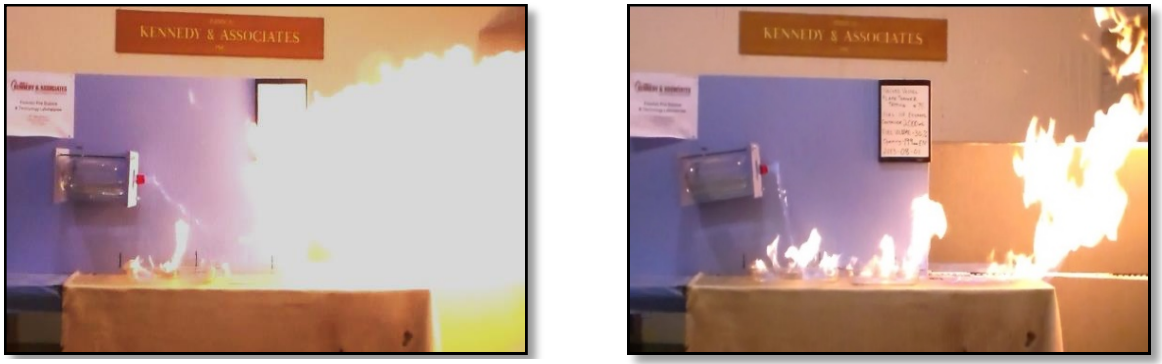
b) Flame front travel up the stream into vessel.

c) Vapor begins ejection as flame enters vessel.

d) Liquid begins ejection as flame front progresses.



e) Vessel approaches maximum pressure. *f) Flame extinguished inside vessel.*



g) Expelled fluids separate from vessel. *h) Liquid continues to pour after NVFTE.*

Figure 6. Representative still photos from digital video of Test 78.
2000 ml plastic bottle with 75 mm neck extension, 19.9 mm opening,
30% filled, slow pour rate, opening not occluded.

Occlusion of the Vessel Opening

Occlusion of the vessel opening refers to the covering of the opening by the liquid fuel during the pouring 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. Total occlusion effectively prevents the flame burning up the vapors emitting from the stream of pouring liquid from entering the vessel and igniting the headspace.

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” (i.e. a long, narrow ejection). 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. One possible outcome is a high volume of fully liquid fuel ejected under a higher pressure. This could be described as a "fire ball" (i.e. a short, wide ejection). This would indicate a very turbulent flow out of the vessel.

Effects of the Flashpoint and Temperature

In 2014 additional testing was done to gain a better understanding of the fire dynamics that were actually occurring *(see Fig. 2)*. Some of the tests used variety of fuels of various flashpoints, and some of the fuels were also tested at multiple temperatures to help determine the relationship between flash point and the occurrence of an NVFTE. All of the tests were conducted using the same vessel under the same conditions. Only the fuel and the temperature of the fuel were varied.

Fuel	**Flash Point (Closed Cup)**	**Fuel Temperature**	**Test 1 NVFTE**	**Test 2 NVFTE**	**Petri Dish Burn**
-	***°C (°F)***	***°C (°F)***	***Yes/No***	***Yes/No***	***Yes/No***
Ethanol Bio-Fuel	13 (55)[5]	7 (44)	No	No	No
		26 (79)	Yes	--	Yes
Diesel, Low Sulfur No. 2	38-62 (100-145)[1]	23 (73)	No	No	No
		66 (150)	Yes*	--	Yes
		82 (180)	No	No	Yes
Gasoline (87 Octane)	-43 (-45)[1]	<-1 (<30)	No	No	Yes
		26 (79)	No	No	Yes
Gasoline (~30% Weathered)	<21 (<70)	26 (79)	No	Yes*	Yes
Kerosene	37 – 65 (100-150)	26 (79)	No	No	No
Gasoline/Kerosene ~50/50	<21 (<70)	26 (79)	Yes	--	Yes

Table 2. Flashpoint and Fuel Temperature
(Continued next page)

Fuel	**Flash Point (Closed Cup)**	**Fuel Temperature**	**Test 1 NVFTE**	**Test 2 NVFTE**	**Petri Dish Burn**
-	***°C (°F)***	***°C (°F)***	***Yes/No***	***Yes/No***	***Yes/No***
Mineral Spirits, Low Odor	40 (104)	26 (79)	No	No	No
Naptha	-22 (-7)	26 (79)	No	Yes	Yes
Acetone	-20 (-4)[7]	23 (73)	Yes	--	Yes
"Solvent Stew" (a mixture of test remnants)	<26 (<79)	26 (79)	Yes	--	Yes
*500 ml Erlenmeyer Flask					

Table 3. Flashpoint and Fuel Temperature
(Continued next page)

These tests were conducted using a 500 ml glass bottle with a square cross section, and a neck 16.4 mm ID x 50 mm. Each fuel was tested once if an NVFTE event occurred on the first attempt, and a second test if not. The fuel was also subjected to an open burn test in a Petri dish.

All fuels below their flash point temperatures did not ignite in either the vessel or the Petri dish.

For fuels above their flashpoint temperature, a different story unfolded. All ignited in the Petri dish, but only some ignited in the bottle. It was then hypothesized that the long narrow neck of the bottle may have acted as a flame arrester in some of the fuel/temperature combinations, or inhibit the inflow of air into the vessel. For those fuels whose flashpoint temperature was significantly lower than the ambient temperature, and thereby generating a higher vapor pressure, this was especially true. Further tests were performed using a 500 ml Erlenmeyer flask (32.4 mm ID opening, roughly 4 X cross sectional area) that produced some positive NVFTE events, indicating this may indeed be the case. More research is needed to confirm this.

OTHER RESEARCH

While 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, static charges in the container, or whether or not gasoline containers can actually rupture and explode during an NVFTE event. We believe that ours is the first research which attempts to understand the phenomenon in full detail. Following is a chronological listing of related research found which includes:

- 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 product recalls.*

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 more than 35 years of experience with investigation, research and litigation cases.

First, it should be noted that while almost 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 Necked Vessel Flame Thrower Effect

1. The temperature of the fuel being above its flashpoint.
2. The vessel must have a spout opening large enough to allow the passage of a flame front through its entire length. Enough residual energy must pass through to ignite the fuel vapor/air mixture it encounters when entering the headspace in the vessel.
3. The vessel opening must have a cross sectional area small enough when compared to the volume of the vessel. It must allow for adequate build-up of pressure within the vessel to expel liquids or droplets.
4. The vessel must have sufficient headspace when the flame front arrives to support adequate combustion to generate sufficient pressure to expel vapors and/or liquids.
5. The vessel has sufficient ignitible vapors (within the ignitible range) to support adequate combustion and generate sufficient pressure to cause an ejection.
6. The vessel has sufficient liquid to be expelled.
7. The contents of the vessel are poured slowly enough to allow the passage of the flame front into the vessel.

Conditions Unfavorable the Necked Vessel Flame Thrower Effect

1. The temperature of the fuel being below its flashpoint.
2. The vessel’s opening is too small and/or the neck is too long. The heat energy of the flame front will be transferred to the interior of the neck thereby quenching the flame, acting as a de facto flame arrester.
3. The vessel opening is too large relative to the volume. The pressure generated will be insufficient to eject liquid or droplets from the vessel.
4. The vessel is completely or nearly full and has insufficient headspace to support enough combustion and provide sufficient pressure to eject liquid or droplets.
5. The vessel has insufficient ignitible vapors (within the ignitible range) to support adequate combustion and generate sufficient pressure to cause an ejection. If the vapor/air mixture in the headspace is too rich or too lean, ignition of the vapors in the headspace will not occur.
6. The vessel has insufficient liquid to be expelled.
7. The contents of the vessel are poured too quickly, causing occlusion of the opening and preventing the passage of the flame front into the vessel.

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. During our independent research 61% of the potential Necked Vessel Flame Thrower Effect test incidents resulted in a Class 0, 1 or 2 event, and did not produce a significant fire danger. The remaining 39% of the test incidents produced a Class 3 or 4 event. If this is representative of events outside of the laboratory, one can understand why few events come to the attention of the public or private sectors 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 attention of fire investigators, fire analysts and fire protection specialists, the courtroom, or onto the evening news.

Additional research is currently under way at JAK&A Laboratories addressing the use of flame arrester type devices to prevent Necked Vessel Flame Thrower Effect type incidents. It is expected that results will be published in the near future.

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