# "HOURGLASS" BURN PATTERNS: A SCIENTIFIC EXPLANATION FOR THEIR FORMATION

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## ABSTRACT

The science of interpreting burn patterns is considered important by fire investigators when establishing a fire's area of origin. When a fire occurs in a room adjacent to a wall or corner, the fire plume often creates damage called "V" patterns. In certain cases, this pattern appears in the shape of an "hourglass" burn pattern. The identification and vector analysis of this specific burn pattern is included in several treatises in the field, including *Kirk's Fire Investigation*[1], *Forensic Fire Scene Reconstruction*[2], and the National Fire Protection Association's *NFPA 921 – Guide for Fire and Explosion Investigation*[3].

The purpose of this paper is to scientifically explain the formation of "hourglass" burn patterns. Both fire testing and mathematical analysis by the authors show that the formation of "hourglass" burn patterns is a direct function of the fire plume's virtual origin, which is mathematically tied to the heat release rate and surface area of the fuel package. Several examples are provided along with engineering calculations.

## INTRODUCTION

The ability to document and interpret fire patterns accurately is essential to investigators reconstructing fire scenes, and they are often the only remaining visible evidence left after a fire is extinguished. Heat transfer is the major cause of change to the exposed surface and appearance of materials during a fire. The surface changes are caused both by direct effects of heat and indirect, e.g., due to thermal expansion and mechanical effects. Fire patterns are formed by the thermal intersection of fire plumes on exposed solid surfaces such as floors, ceilings, and walls. These burn patterns are influenced by a number of variables including the available fuel load, ventilation, and the physical configurations of the room. Many common combustible materials and ignitable liquids can produce these fire plumes and their resulting damage.

### Fire Plumes

The single most important factor in fire scene reconstruction is the ***fire plume,*** which is usually a simple flaming fuel source emitting a vertical column of flames and hot products of

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[*] University of Tennessee, Department of Electrical and Computer Engineering, 301 Ferris Hall, 1508 Middle Drive, Knoxville, Tennessee 37996-2100, telephone numbers (865) 974-8051, (865) 974-5483 (fax), email: icove@utk.edu

[+] Fire-Ex Forensics, Inc., 3505 Sonoma Blvd., PMB314 #20, Vallejo, California 94590, telephone numbers (707) 643-4672, (707) 643-4682 (fax), email: jddehaan@inreach.com combustion.[4] Fire plumes can originate from any fuel combination that has sufficient heat release rates to generate a buoyant column of flames and smoke. Fire plumes result from any significant fire. Floor-level pools of ignitable liquids can produce them; however, many combustible solids, including certain types of foam mattresses and plastics, melt and collapse while burning and behave like liquid fuels.

The shape of burning pools producing fire plumes depends upon several variables including the geometry of the containment of the pool, the type of substrate on which the pool is resting, and, in some cases, the external winds. Since fire plumes are three-dimensional, their location can often be determined and documented by evaluating the patterns of heat transfer, flame spread, and smoke damage they cause to adjacent flooring, wall, and ceiling surfaces as illustrated in Figure 1. A fire investigator can gain additional insight through a more fundamental understanding of the nature, physics, and heat transfer characteristics of these fire plumes.

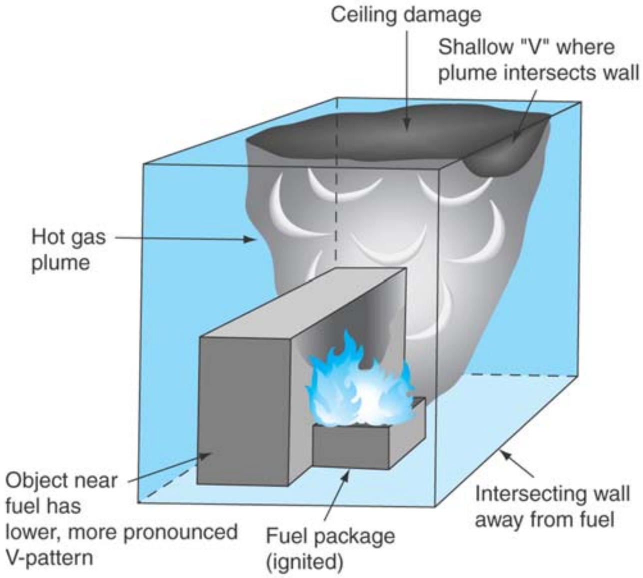


**Figure 1. Schematic representation of the formation of "V" patterns by a fire plumes.**
Source: D.J. Icove and J.D. DeHaan. "*Forensic Fire Scene Reconstruction*,"
Prentice Hall, Upper Saddle River, NJ, 2004.

## Virtual Origin

The ***virtual origin*** is a focal point located along the plume's centerline and is the equivalent point source height of a finite area fire.[5] Its location is a point above the fire plume where flames appear to originate, measured from the top burning surface of the fuel package.

Depending on the heat release rate, the equivalent diameter of the surface of the burning fuel package, and the level of this package above the floor, the virtual origin can be either lower or higher than floor level. Shown in Figure 2 are the two common locations for the virtual origin, above and below the burning surface of the fuel package.

The virtual origin can be mathematically calculated, and its location can be helpful in reconstructing and documenting the fire's virtual source, point of origin, area, and direction of travel. The virtual origin is also used in some calculations for the measurement of the fire plume flame height.

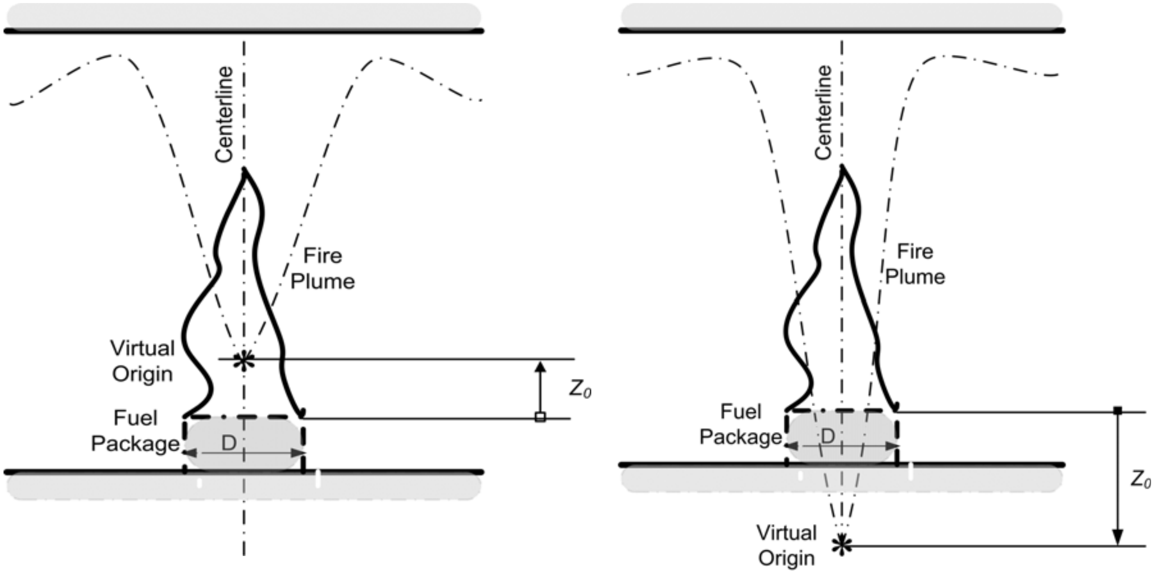
The calculation for virtual origin, as taken from the *Heskestad* equation,

$$Z_0 = 0.083\,\dot{Q}^{2/5} - 1.02\,D$$

where

$Z_0$ = Virtual origin (m)
$D$ = Equivalent diameter (m)
$\dot{Q}$ = Heat release rate (kW).

As can see from this mathematical relationship, fires with smaller equivalent diameters and high heat release rates tend to have positive values for their virtual origin (Figure 2 (a)). However, lower heat release rate fires with broader equivalent diameters tend to have negative values for their virtual origin (Figure 2(b)).



(a) Positive value for virtual origin places it above the fuel package surface.

(b) Negative value for virtual origin places it below the fuel package surface.

**Figure 2. The relationship of the virtual origin to the fire plume.**
Source: D.J. Icove and J.D. DeHaan. "*Forensic Fire Scene Reconstruction*," Prentice Hall, Upper Saddle River, NJ, 2004.

For example, a combustible fire with a high heat release rate and narrow diameter fuel package will typically have a positive value for the virtual origin, indicating it is located along the centerline above the burning surface of the fuel package. This relationship can be further explored in the graph (Figure 3) plotting the relationship of the virtual origin with changes to the heat release rate and effective diameter of the burning fuel.

Shown in Figure 4 are the results from an actual fire test. In this case, a 0.31 m x 0.61 m (12 in x 24 in) cardboard box with an estimated heat release rate of 150 kW having an effective diameter of 0.49 m (1.61 ft), produces at virtual origin with a positive value of 0.12 m (0.39 ft or 4.7 in), indicating it is located above the level of the burning fuel package.

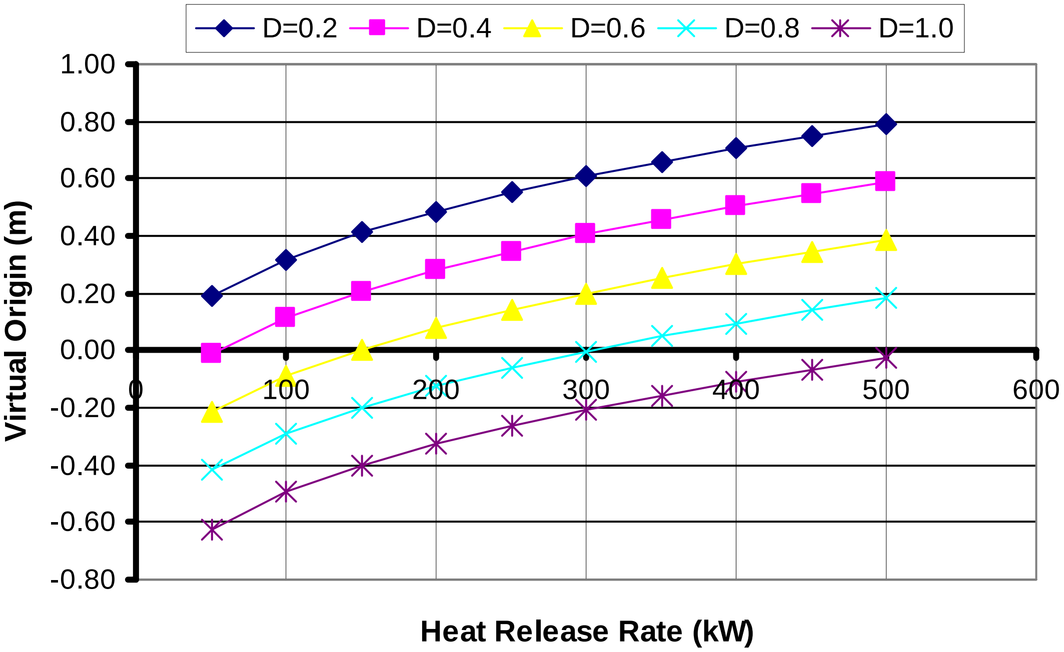
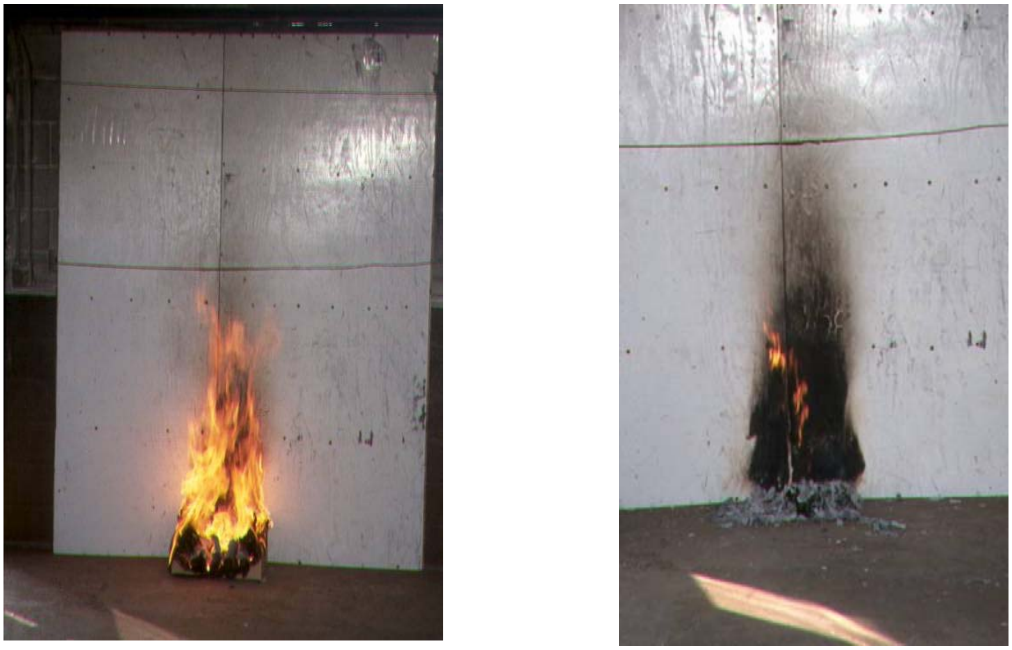


**Figure 3.** **Plot of the relationship of the virtual origin with changes to the heat release rate and effective diameter of the burning fuel.**



(a) (b)

**Figure 4. An inverted "V" shaped fire pattern during and at self-extinguishment with an equivalent diameter of 0.49 m (1.61 ft) placing the virtual origin at 0.12 m (0.39 ft).**
Source: Photos courtesy of Susan Sherwin, Maricopa County Attorney's Office.

## ”V” Patterns

The impingement, intensity, and direction of the fire plume’s travel form ***lines or areas of demarcation*** on walls, ceilings, floors, and other materials. These demarcations occur in locations where a combination of smoke, heat, and flames impinge upon materials, forming intersections of affected and unaffected areas. Common examples include smoke layers deposited on walls and plume patterns on walls.

Demarcations can vary depending on the type of exposed material, fire temperature, rate of heat release, and ventilation. Areas of material loss are helpful in determining demarcations. They may be simply deposits on the surfaces or the result of heat transfer causing scorching, melting, charring, or ignition at the affected area.

As the hot gases and smoke rise from a fire, they mix with surrounding air, with the mixing zone becoming wider as hot gases rise above the fuel. Entrainment mixes and spreads the rising column so it forms a “V” approximately 30° in width (i.e., half-angle of 15º) if unconfined in still air from a turbulent of diffusion fire.[6] As the fire gases mix, they are diluted and cooled. The diameter of the hottest part of the plume along the centerline becomes smaller with increasing height.

Testing by the Factory Mutual Research Corporation (FMRC) reveals greater scientific insight into the formation of V patterns. In FMRC’s 25-ft corner tests,[7] a closer examination of a fire plume’s lines of demarcation reveals distinct areas of damage to the wall surfaces, also known as the ***fire propagation boundary***. This boundary is a visually distinguishable line where the heavy pyrolysis of the surface ends.

Actual fire testing by FMRC documents the close correlation of the fire propagation boundary with the ***critical heat flux boundary***. This is the location of the boundary where the minimum heat flux is at or below the point where a flammable vapor–air mixture is produced by pyrolysis at the surface of the solid (See the SFPE Handbook, 3rd ed, Figure 3-4.17). Critical heat fluxes have also been experimentally determined by successive exposures of material samples to progressively decreasing incident heat fluxes until ignition no longer takes place.[8]

Analyzing the shape of fire patterns caused by plumes can provide valuable information. For example, the greatest ceiling damage is often in the plume impingement area directly above the fuel source (as in Figure 1), a point from which a gas-movement vector points directly back to the fire’s origin. In simple two-dimensional views where the fire plume comes into contact with and damage wall surfaces, damage patterns forming lines of demarcation frequently appear. These lines are often referred to as ***V-shaped fire patterns***, based on their characteristic upward-sweeping shape.

The references *NFPA 921, Kirk’s Fire Investigation,* and *Forensic Fire Scene Reconstruction* have dispelled past misconceptions regarding the shape and geometry of V patterns, once thought to relate to the rapidity of fire growth. The shape of a V pattern is actually related to the heat release rate, geometry of the fuel, ventilation effects, ignitability and combustibility of affected surfaces, and intersection with horizontal surfaces.

The key to understand the lines and angles of these lines of demarcation is to allow them to assist in documenting the fire plumes. Several mathematical relationships exist that provide an insight into documenting and analyzing the features of fire plume height, temperature, velocity, vortex shedding frequency[9], and virtual origin.[10] Many of these relationships are included in the previously mentioned references, National Institute of Standards and Technology (NIST) on-line reports, and the Society of Fire Protection Engineers (SFPE) Handbook.

## FORMATION OF THE "HOURGLASS"

When a fuel package burns in a room adjacent to a wall or corner, the fire plume often creates damage termed a "V" pattern. In certain cases, this pattern appears in the shape of an "hourglass" burn pattern. Both fire testing and mathematical analysis by the authors show that the formation of "hourglass" burn patterns is a direct function of the fire plume's virtual origin, which is mathematically tied to the heat release rate and surface area of the fuel package.

### Fire Testing

Tests to explore fire pattern generation were conducted with the assistance of NIST[11], the Federal Emergency Management Agency's U.S. Fire Administration (FEMA/USFA)[12], and the U.S. Tennessee Valley Authority (TVA) Police[13] in Florence, Alabama. The U.S. TVA Police concentrated on extending the results of fire pattern burn testing on larger-scale structures, while NIST and FEMA worked on the single-family dwelling scenarios.

The primary goals of these tests included demonstrating the production of fire burn patterns, exploring fire scene evidence and documentation techniques, and validating basic fire modeling—all concepts that form the underlying theme for forensic fire scene reconstruction. One series of test burns by Icove included the simulation of arson fires using plastic containers of ignitable liquids, which are sometimes used by arsonists when setting fires to structures.[14]

To simulate an arson attack, a typical firebomb consisting of a 3.8-liter (1-gal) plastic container filled with unleaded gasoline was placed in the corner of the facility's main assembly room. The main room floor was covered with institutional-grade synthetic carpeting. A floor plan of the building appears in Figure 5.

The firebomb was remotely ignited with an electric match, with the resulting fire burning for approximately 300 seconds and then self-extinguishing, leaving a 0.457 m (1.5 ft) diameter circular burned area on the carpet. Three thermocouple trees recorded the room temperature profiles.

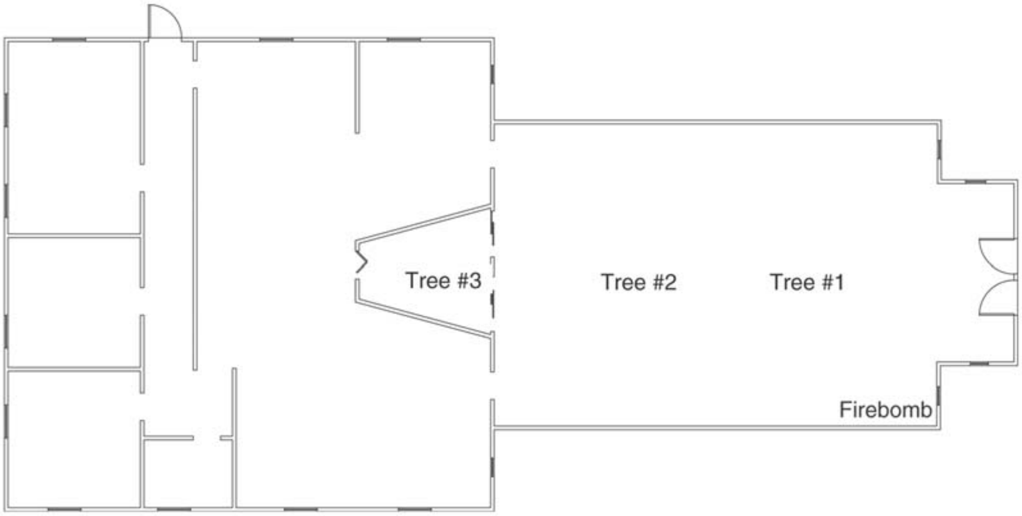


**Figure 5. Floorplan showing placement of the firebomb and three thermocouple trees.**
Source: D.J. Icove and J.D. DeHaan. "*Forensic Fire Scene Reconstruction*,"
Prentice Hall, Upper Saddle River, NJ, 2004.

The post-fire damage patterns from the test are depicted in Figure 6. The exact location of the firebomb and its subsequent burning pool diameter are indicated. Shown below in Figure 7 is the photographic documentation in firebomb test case of the experimental formation of an hourglass burn pattern formed by a single fire plume. The photo to the left is an analysis of the common fire pattern indicators consisting of (1) demarcation, (2) calcination, (3) loss of material, (4) fractured glass, (5) ignitable liquid burn pattern on carpet, (6) penetration into the ceiling, and (7) area of clean burn. The comparison photo on the right graphically illustrates and overlays the schematic outline of the fire plume, fuel package, and virtual origin beneath the floor.

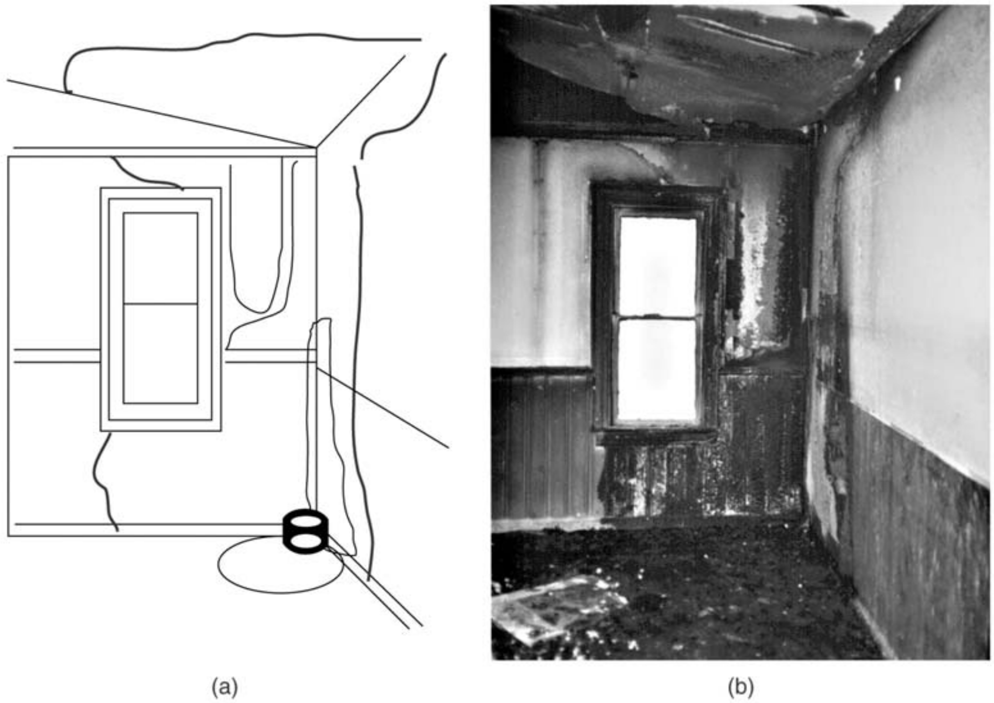


**Figure 6. (a) Sketch and (b) photograph of post fire damage patterns showing the location of the firebomb, burning fire pool, and significant lines and areas of demarcations.**
Source: D.J. Icove and J.D. DeHaan. "*Forensic Fire Scene Reconstruction*," Prentice Hall, Upper Saddle River, NJ, 2004.

**Estimated Heat Release Rate**

Without taking into consideration the impact of the carpeted floor surface, the peak estimated heat release rate, $\dot{Q}$, for the gasoline pool fire can be calculated as:

Heat release rate $\dot{Q} = \dot{m}'' \Delta h_c A$

Area of the burning pool $A = (3.1415/4)\,(0.457^2) = 0.164 \text{ m}^2$

Mass flux for gasoline $\dot{m}'' = 0.036 \text{ kg/m}^2\text{-s}$

Heat of combustion (gasoline) $\Delta h_c = 43.7 \text{ MJ/kg}$

Heat release rate $\dot{Q} = (0.036)\,(43700)\,(0.164) = 258 \text{ kW}$

## Virtual Origin

A carpeted rather than a smooth surface would impact the burning rates of liquid fuels, such as gasoline. In small liquid pool fires, such as in spilled fuels on carpeted surfaces, researchers now report that their burning rates are less than that of a comparable free-burning pool fire.[15] Based on this information, 250 kW will be used in these calculations.

The calculation for the location of the virtual origin confirms that it is above the fuel surface, in this case the floor. Using the heat release rate of 250 kW for a 0.457 m (1.5 ft) diameter gasoline fire on the carpeted floor, the virtual origin, as taken from the *Heskestad* equation, is calculated as:

Virtual origin $Z_0 = 0.083\ \dot{Q}^{2/5} - 1.02\ D$

Equivalent diameter $D\ = 0.457\ \text{m}$

Total heat release rate $\dot{Q} = 250\, kW$

Virtual origin $Z_0 = (0.082)(250)^{2/5} - (1.02)(0.457)$

$$= 0.746 -\ 0.466 = 0.28\, m\ (0.92\, ft)$$

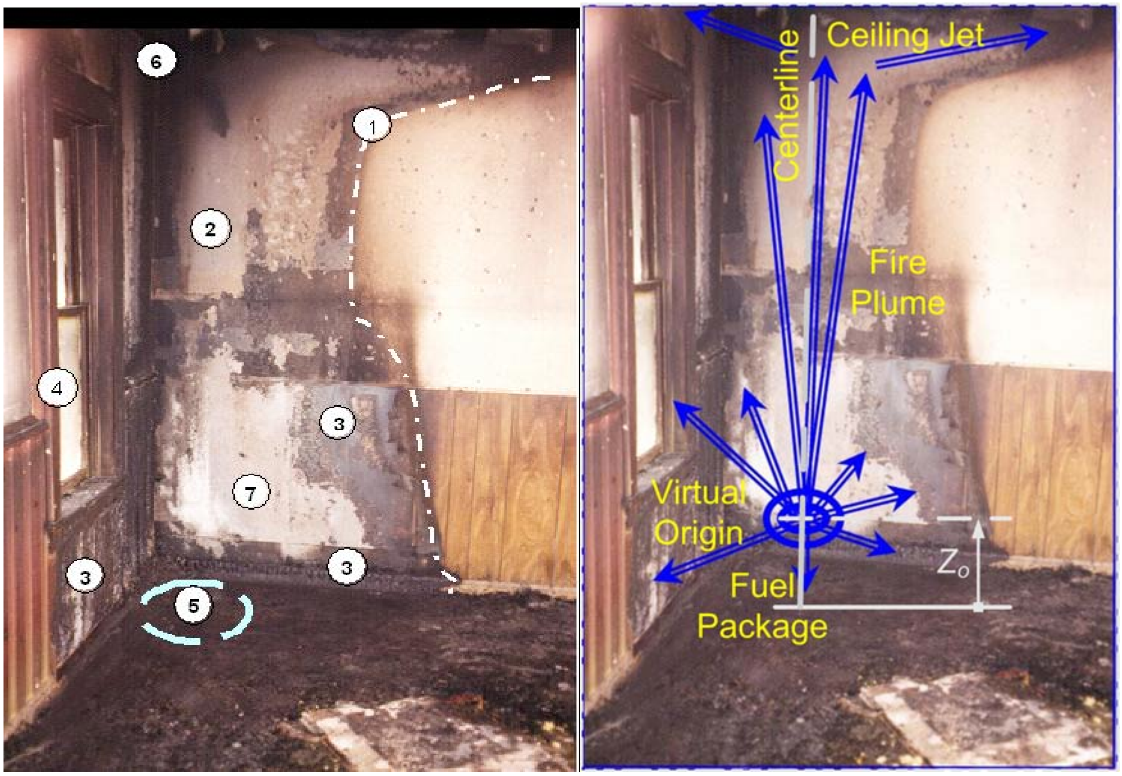
For this case example, $Z_0$ is determined to be 0.28 m (0.92 ft or 11 in), confirming that its is above the floor level as can be shown in Figure 7. Research by Heskestad reveals that a fuel releasing a high energy over a small area, such as in this case example, is more likely to produce a virtual origin above the floor level.

Fire investigators can also use a vector analysis in this firebomb test case to better understand and interpret the combined movement and intensity of the fire plume that created the pattern damage shown in Figure 7. Note that the vectors originate from an area above where the firebomb was located on the floor, closely corresponding to the location of the theoretical virtual origin.

Some generalities are gleaned regarding hourglass burn patterns by taking a combined look at of the relationship of the virtual origin to the fire plume (Figure 2), the incremental analysis of the Heskestad equation (Figure 3), and the test fire damage (Figure 7). This information shows the direct relationship on the virtual origin by increasing the heat release rate and/or decreasing the size of the equivalent diameter. This relationship may be thought of as being dependent on the ‘density’ of heat release rate per unit surface area of the fuel.

For a given effective diameter of the fuel package, the higher the heat release rate is, the more ‘positive’ (above the floor) the virtual origin becomes. A high energy density fire produces strong entrainment near its base, which initially confines the high temperature gases towards the centerline producing the apparent narrowing of the plume above the fuel package, causing the distinct hourglass pattern.

Fire investigators who will be routinely conducting calculations involving fire plume relationships are suggested to obtain, study, and use the Fire Dynamics Tools (FDT$^s$), which are a set of spreadsheets developed for fire hazard analysis by the U.S. Nuclear Regulatory Commission (NRC).[16] Both the documentation and spreadsheets are available at no charge on the NRC’s Internet website.



(a) (b)

**Figure 7. Experimental formation of an "Hourglass" burn pattern by a fire plume (a) Analysis of fire pattern indicators, (b) Graphical location of virtual origin with respect to fuel package and ceiling jet.**

Source: D.J. Icove and J.D. DeHaan. "*Forensic Fire Scene Reconstruction*," Prentice Hall, Upper Saddle River, NJ, 2004.

## CONCLUSIONS

Fire pattern damage analysis is a vital investigative technique for fire scene reconstruction. The visual interpretation of damage created by fire plumes can isolate and accurately identify the area of fire origin.

Locating and identifying the first fuel package ignited is a critical step in the accurate reconstruction of any fire incident. Careful analysis of fire patterns can significantly aid the scene investigator in this effort. Because effects like charring, melting, ignition, and protection are predictable, their location and distribution offer a sound basis for locating fuel packages, which can be confirmed by interviews or pre-fire photos.

Systematic steps relying upon the placement of the fire plume and the calculation of its virtual origin can be used by fire investigators to support and document thermal damage patterns, identify the fire's direction and intensity, confirm significant witness observations, and verify the results of fire modeling. These systematic steps should invoke the scientific method to test and evaluate various hypotheses of the fire's origin and spread.

From these observations, the authors conclude the following:

- Formation of patterns on walls follows well-established heat transfer laws.
- The areas and lines of demarcation within the V pattern can reveal the

temperature distribution within the plume to help confirm the location and source of the fuel package.

- The presence of an hourglass pattern typically represents a high energy fire with a small effective diameter and strong entrainment near its base – this may be a pattern from a fuel package such as a urethane foam cushion or an ignitable liquid pool.
- An inverted V pattern (sometimes termed an ‘A-pattern’) indicates a lower energy fuel package with a wider effective diameter.
- Fire hazard analysis tools, such as the NRC’s Fire Dynamics Tools, can be effective in evaluating the various properties of fire plumes, including virtual origin, flame height, estimated heat release rates, and duration.

## ACKNOWLEDGEMENT

The authors thank Dr. Vytenis Babrauskas, President, Fire Science and Technology, Inc., Issaquah, Washington, for his guidance and assistance in the peer review of this paper.

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