Forensic Architecture

# The Use of White Phosphorus Munitions in Urban Environments:

## An Effects-Based Analysis

Prepared in collaboration with Situ Studio

SITU STUDIO

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Part of the European Research Council project Forensic Architecture
Centre for Research Architecture, Goldsmiths, University of London.

www.forensic-architecture.org

# Contents

## i. About the report

The report focuses on the characteristic behavior and effects of airburst white phosphorus munitions in urban environments. It was produced at the request of attorney Michael Sfard.

## ii. About the authors

Forensic Architecture is a research project based at the Centre for Research Architecture, Goldsmiths, University of London (UK).

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## iii. Acknowledgements

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www.forensic-architecture.org

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# 1. Introduction

## 1.1 White phosphorus, its harmful effects, and its military uses

White phosphorus is a highly flammable chemical substance made from a common allotrope of phosphorus. It ignites spontaneously upon contact with air, producing a dense white smoke.

White phosphorus is considered a toxic substance,[1] capable of causing severe injuries to internal organs when absorbed through skin, ingested, or to lesser degree when inhaled. When burning particles of white phosphorus come into contact with skin, they produce thermal and chemical burns. Because of its high solubility in fat, white phosphorus has the potential for deep dermal penetration and can rapidly burn exposed body areas down to the bone.[2] Burn wounds can also re-ignite when bandages are removed and burnt areas re-exposed to oxygen.

Within military context, white phosphorus (WP) can be found in a variety of munitions, such as grenades, mortars, and artillery shells. These munitions are used for four distinct purposes:

- Illumination - The bright white light created by the burning WP can be used to illuminate large areas at night.
- Signaling - The dense smoke produced by WP can be used to signal a target.
- Screening - WP smoke can also be used to create a thick smoke-screen to hide the movement of people and vehicles in open or built environments.
- Incendiary - WP munitions can be used to set targets and combat areas on fire.[3]

Depending on the situation and objectives, military forces may choose to deploy a particular WP ammunition because of its specific design and characteristics, rather than another. Regardless of the primary military purpose for using a WP ammunition, a range of secondary effects can be generated that are specific to the properties of white phosphorus itself. In particular, when WP munitions are deployed in urban

1 ”Toxicological Profile for White Phosphorus”. Prepared by Sciences International, Inc. for U.S. Department of Health and Human Services, 1997.

2 Global Security [online] http://www.globalsecurity.org/military/systems/munitions/wp.htm/

3 Ibid.

environments for signaling or screening purposes, they can produce incendiary effects that may harm civilian persons and objects. These secondary effects are the primary focus of this report.

## 1.2 Objectives of the report

The report presents an Effects-Based Analysis (EBA)[4] of the American-made M825 WP Smoke projectile.

The M825 WP has been used in urban contexts during the assaults on Fallujah (by the United States military in 2004) and Gaza (by the Israel military in 2009). Although primarily designed to produce smoke-screens, the secondary effects of WP munitions have been widely acknowledged and documented. These include: ignition of multiple fires in the impact area, direct strike on civilians by falling projectile debris, and long-term contamination of the environment.[5]

The main objectives of this report are to analyze the incendiary effects of the M825 WP projectile when deployed in urban environments, and to evaluate the civilian exposure that may be expected in such scenarios.

Effects in urban environments are due to specific characteristics of, on the one hand, the projectile itself, and on the other hand, the built environment impacted. Therefore, the methods employed in this report combine ballistic simulation with spatial analysis and urban reconstruction. After detailing the characteristics and the functioning of the M825 WP (Section 2), the report analyzes the interplay between the projectile and a given built environment at both the urban scale (Section 3) and the architectural scale (Section 4). The specific objectives of the report are:

- To evaluate the Coverage Area of the M825 WP projectile.
- To identify the range of parameters, controllable and uncontrollable, at play when the projectile is deployed over typical urban environments.
- To catalog types of damage to objects and persons in urban contexts and to quantify civilian exposure across a range of contexts.

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4 Contrary to an analysis of the projectile's behaviour and performance based on its design and intended military purposes, this Effects-Based Analysis (EBA) focuses on the actual overall effects of the M825 WP projectile when deployed in specific contexts.

5 Human Rights Watch, "Rain of Fire" report (2009).
New Weapons Research Group, "Potential Health Risks For The Population Attacked With White Phosphorus Ammunitions In Gaza - Ammunitions In Use, On The Ground, January 2009" (2010).

## 1.3 Sources of information

Three principal sources of information have been used in the formulation of this report.

- Military field manual and documentation of the M825 WP projectile.[6]
- Photographic and video documentation of M825 WP deployment and its subsequent effects, in the cases of Fallujah (2004) and Gaza (2009).
- Reports of post-combat site surveys in both cities conducted by independently commissioned non-governmental organizations.[7]
- Expertise on the military use of white phosphorus by Chris Cobb-Smith, weapons expert and safety and security advisor to the International News Safety Institute.

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6 Headquarters, Department of the [U.S.] Army, "Tactics, Techniques, and Procedures for Field Artillery Manual Cannon Gunnery" (FM 6-40 MCWP 3-1.6.19), April 1996.

Headquarters, Department of the [U.S.] Army, "Technical Manual, Army Ammunition Data Sheets" (TM 43-0001-28), April 1994 (Change 11: October 2003). P. 3-165.

7 Human Rights Watch, "Rain of Fire" report (2009).

Amnesty international, "Israel used white phosphorus in Gaza civilian areas" (Press release, 19 January 2009).

# 2. M825 WP

## 2.1 Overview of the projectile

The M825 WP is a 155mm artillery projectile, designed to produce smoke-screens of 5-15 minutes in duration.[8] Its two main components are the projectile carrier – a hollow forged steel shell – and the payload – consisting of 116 white phosphorus wedges.[9]

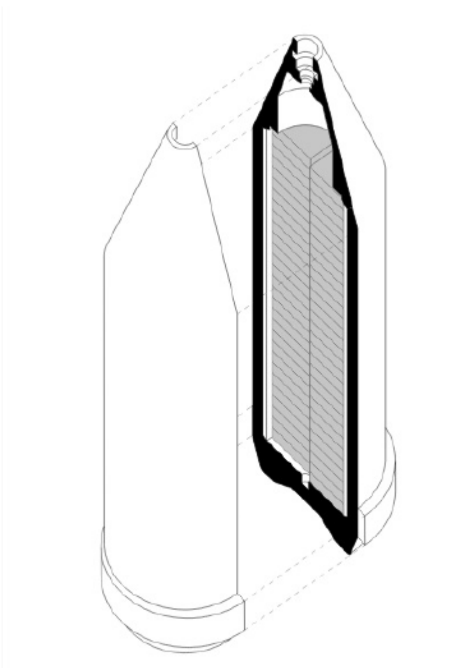
Typically fired from 155mm howitzers, with an effective range of between 3 and 18 km, the M825 WP generally bursts between 50 and 250 meters above ground: a timed charge at the front of the shell is activated and the projectile releases the 116 white phosphorus wedges, which fall to the ground within an elliptical area of up to 200 meters in the long axis.

**Figure 1** - Burst of M825 WP rounds
(Northern Gaza strip,12 Jan 2009 - © Menahem Kahana / AFP)

8 Also in use in military arsenals is the M825A1, a more recent version of the M825 projectile, containing "an improved payload and a new base which have corrected the M825 flight instability." (ARMY TM-9-1025-211-10). The analysis conducted in this report applies to both models.

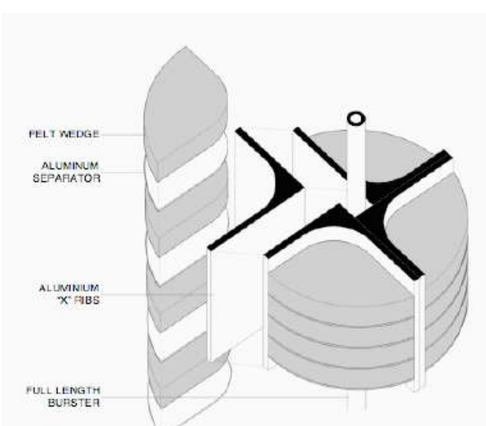
9 Headquarters, Department of the [U.S.] Army, "Technical Manual, Army Ammunition Data Sheets" (TM 43-0001-28), April 1994 (Change 11: October 2003). P. 3-165.

## 2.2 Specifications



| | |
|---|---|
| Type | Smoke, WP |
| Weight | 102.6 lb |
| Length w/fuze | |
| M825 | 35.4 in |
| M825A1 | 34.9 in |
| Body Material | Forged steel/aluminum |
| Color | |
| M825 | Light green w/yellow band and light red markings |
| M825A1 | Similar to M825 and a red band near top of projectile |
| Payload and Weight | 116 felt submunitions saturated with 12.75 lb of WP |
| Burster | Composition A-5, 21.2g |

**Figure 2** - M825 WP projectile diagram and specifications




| | |
|---|---|
| Count | 116 |
| Weight | 100g |
| Chemical Composition | $P_4$ |
| Burn Temperature | 1500° F |
| Burn Duration | 5-15 min |

**Figure 3** - WP wedges diagram and specifications

## 2.3 Smoke and incendiary effect

Encased in a hermetically sealed canister, the 116 wedges are made from felt and saturated with 0.6 ounces of white phosphorus each.[10] When the projectile bursts, the wedges are exposed to the air and begin to burn emitting a thick white smoke as they fall to the ground. The smoke lasts for 5-10 minutes unless oxygen is withdrawn by flooding or smothering the wedges.

Charred wedges retain up to 15% of their white phosphorus content and can re-ignite if the felt is crushed or re-exposed to the atmosphere.[11] Dormant wedges can reignite several weeks after having been deployed. The wedges burn at 1500 degrees Fahrenheit and can set fire to objects they come into contact with.[12] When wedges come into direct contact with people, they can burn through clothing and continue burning through skin, right down to the bone causing both thermal and chemical injuries.

The incendiary effect of the burning white phosphorus wedges accompanies any employment of the M825 WP, regardless of its intended military purpose.

**Figure 4** - Re-ignited charred white phosphorus wedge (Photo: B'Tselem)

10 Headquarters, Department of the [U.S.] Army, ibid.

11 Department of the Army, Pamphlet 385–63 - Safety / Range Safety. Chapter 11.

12 Human Rights Watch, "Rain of Fire" report. p.3.

# 3. Urban Effects

## 3.1 Objectives and methods

In this section, the interplay between a single M825 WP round and a given built environment is examined at the scale of an urban neighborhood. This examination proceeds according to the following steps:

- Photographic and video documentation of M825 WP rounds is analyzed: the initial parameters necessary to model and simulate the ballistic behavior of the projectile are identified; and a range of values for these parameters, either cited in military documents or effectively verifiable in images, is established.
- A parametric model is constructed accordingly. Once the initial parameters are set, the computer-assisted model simulates the dispersal of the 116 wedges until they intersect the ground plane. The resulting Coverage Area is then circumscribed and dimensioned. Several simulations are run and a range of values for the Coverage Area of the M825 WP is established.
- Typical Coverage Areas are mapped onto the built fabric of a given urban neighborhood. When set against demographic statistics and land use of the neighborhood considered, these Coverage Areas allow to evaluate the extent of the civilian exposure resulting from a single M825 WP round.

## 3.2 Photographic analysis

Post-burst characteristics of the M825 WP projectile are documented here and used throughout the report to model the dispersal of the 116 WP wedges.

The point of burst and the subsequent trajectories of the wedges are both clearly identifiable in images of an airburst WP round, respectively as a dense cloud and as thin trails of white smoke in the air. The height of burst can therefore be inferred and approximated using the vertical measurement of buildings identifiable in the image as references. An indication of the projectile's initial trajectory is established by tracking the smoke trails of the wedges as they fall.

The values of burst height and trajectory angles derived from measurements conducted on these images are set against the reference values to be found in the relevant military documents.[13] Together they establish a range of values used in the parametric model. The various M825 WP rounds analyzed are classified into two types, according to the distinction mentioned in artillery field manuals between low-angle fire (below 45°) and high-angle fire (above 45°).

Each of the images analyzed in the following set is marked with indicative values for three variables: Height of Burst (HoB, in multiple of 10m), Opening Angle of the cone of dispersion of wedges ($\alpha$, in multiple of 5°), and Inclination ($\beta$, in multiple of 5°).

It should be noted that the Opening Angles and Inclinations documented in all available photographs may differ slightly from the actual Angles of the round considered because of the orientation of the line of fire in relation to the picture plane of the image.


**Figure 5** - High-angle fire : example 1 (Gaza, 3 Jan 2009 - © Yannis Behrakis / Reuters)

13 Headquarters, Department of the [U.S.] Army, "Tactics, Techniques, and Procedures for Field Artillery Manual Cannon Gunnery" (FM 6-40 MCWP 3-1.6.19), April 1996.


**Figure 6** - High-angle fire : example 2 (Fallujah, Nov 2004 - © CNN)


**Figure 7** - High-angle fire : example 3 (Gaza, 8 Jan 2009 - © Mohammed Salem / Reuters)


**Figure 8** - Low-angle fire : example 1 (Gaza, 12 Jan 2009 - © David Silverman / Getty Images)

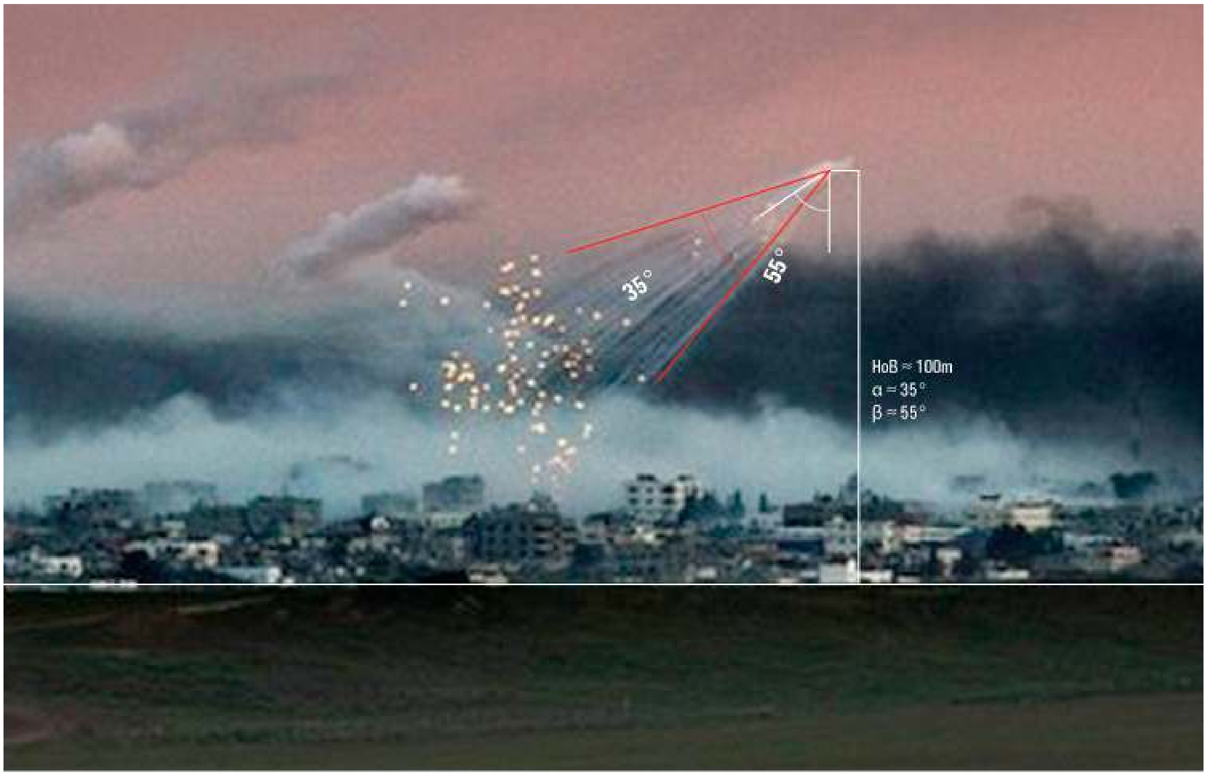



**Figure 9** - Low-angle fire : example 2 (Gaza, 4 Jan 2009 - © Eliyahu Ben Igal / Jini / Associated Press)


**Figure 10** - Low-angle fire ; example 3 (Fallujah, Nov 2004 - © RAI News 24)

*NOTE: More examples of photographic analysis are available in the online version of this report (http://www.forensic-architecture.org/WhitePhosphorus/?pageid=4).*

## 3.3 Burst Dynamics

A series of variables are identified and isolated for their utility in creating a parametric model to run iterative three-dimensional burst simulations as well as to analyze video footage. The model is constructed to include the following parameters, all of which can be controlled and then run iteratively and quantitatively analyzed:

- Height of Burst ( HoB ): Height from ground plane at which a timed fuse separates the shell and activates the charge that initiates burst.
- Opening Angle ( $\alpha$ ): Angle at which wedges emerge from the shell upon bursting. This angle can change depending on the type of charge chosen for a particular projectile.

- Inclination ( $\beta$ ): Angle at which the projectile is approaching the ground at moment of burst. This can be understood as a measurement in degrees between the bisector of the opening angle and a line normal to the ground plane.
- Plane Displacement ( $\gamma$ ): Angle between the vertical plane of the line of fire and the vertical plane of view. This parameter, while not linked to projectile behavior, is necessary for establishing the actual trajectory of the projectile based on how it appears on the picture plane of an image.

Ultimately, the parametric model constructed and used in this report functions as a tool to measure and quantify characteristics of projectile behavior in both abstract and contextualized scenarios. It should be noted that simulations conducted for this report do not factor in meteorological conditions such as wind and precipitation, which can also influence projectile behavior.

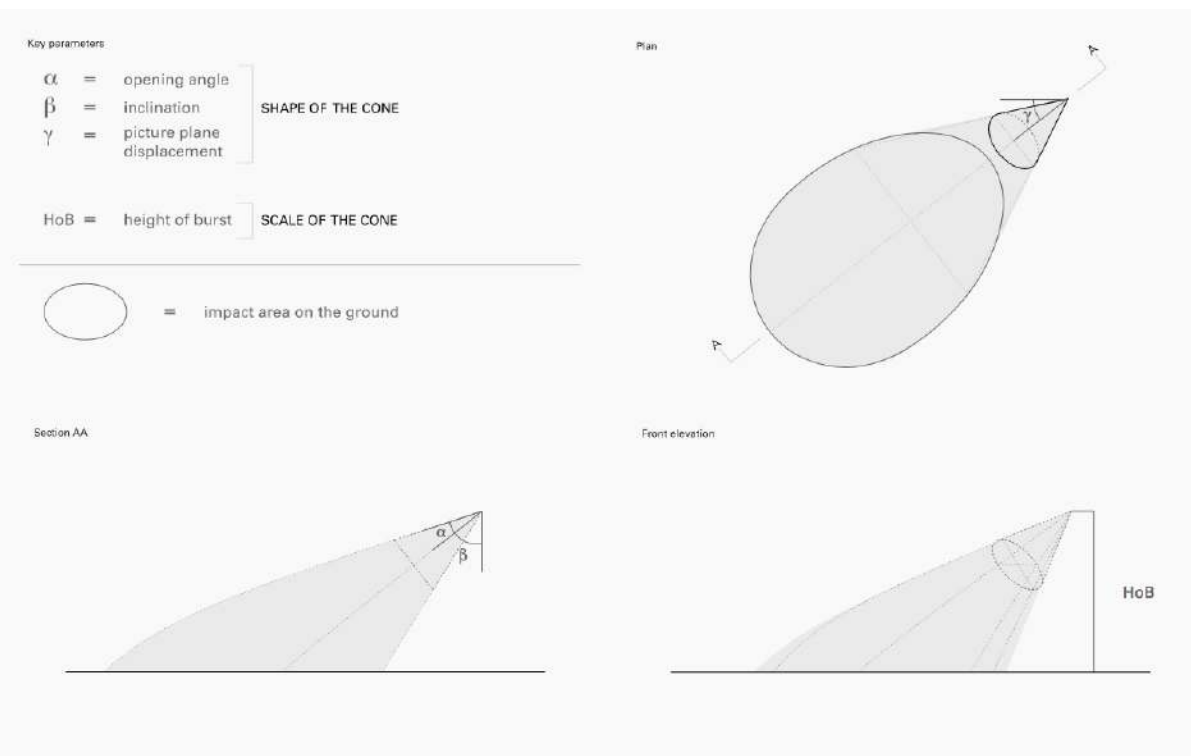



**Figure 11** - Key parameters of the computer-assisted model and diagrams

## 3.4 Coverage Area

The analysis undertaken to evaluate the Coverage Area of the M825 WP projectile is separated into two distinct sets of simulations:

- Low Angle/High Angle: The first set simulates the ballistic behavior of the M825 WP in a low-angle and in a high-angle fire scenario, by matching the parameters used in the model with those identifiable in the video documentation of a typical example of each scenario. Once the simulation is run, the Coverage Area is established for each.
- Area Spectrum: The second set of simulations focuses on the minimal and maximal dimensions of the elliptic Coverage Area within which an M825 WP round may distribute its wedges. To illustrate the burst dynamics in a maximal Coverage Area scenario, the variables of the parametric model are adjusted to produce an ellipse of length 200m in the long axis, so as to match the maximum dimension cited in military documents. The minimal Coverage Area, as far as could be established at the time of this report, is not officially documented in field manuals or munitions specifications. Thus, to simulate the minimal Coverage Area, variables were chosen within the range of observable behavior in archival footage.

These maximal and minimal Coverage Areas establish the spectrum of areas that can be covered by a single M825 WP round, and are limits considered for the estimation of civilian exposure in the following section.

*NOTE: The analysis in the following pages is best viewed as a video animation on the online version of this report (http://www.forensic-architecture.org/WhitePhosphorus/?pageid=7)*


**Figure 12** - Video Analysis 1: Low Angle Fire (Gaza, Jan 2009. Source footage: Al-Jazeera [CC])

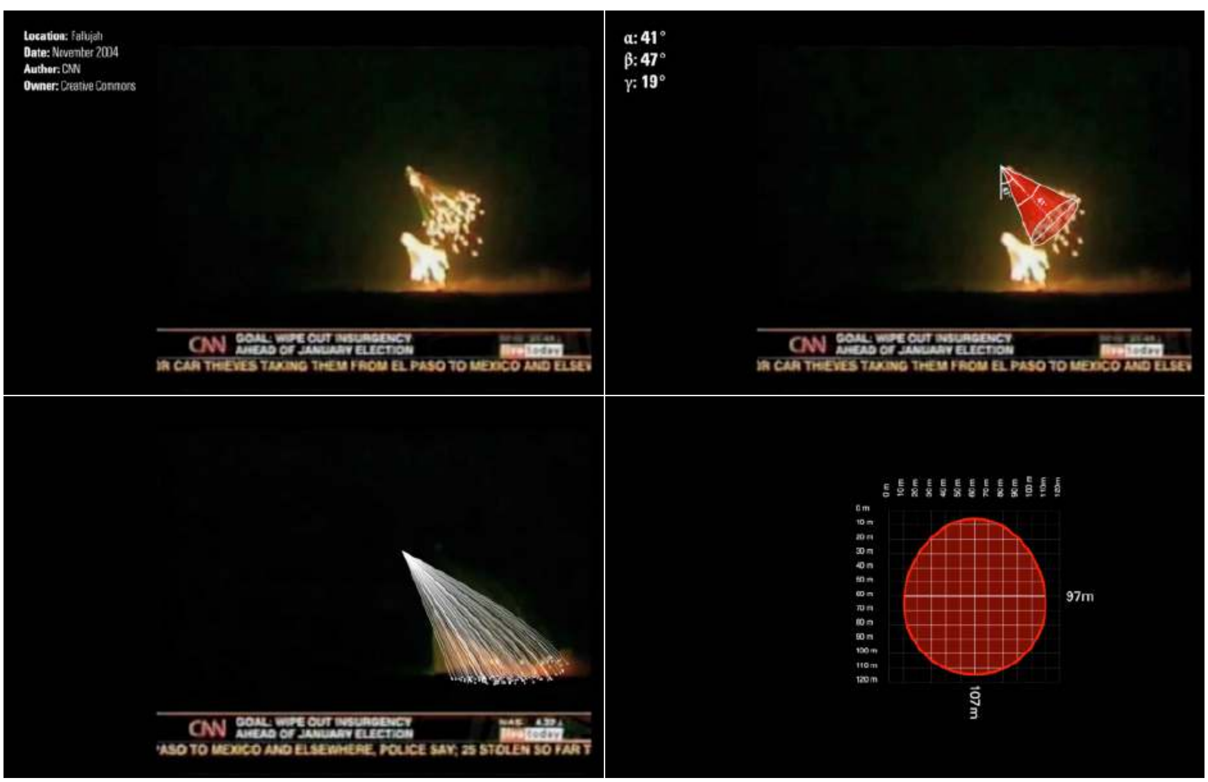



**Figure 13** - Video Analysis 2: High Angle Fire (Fallujah, Nov 2004. Source footage: ©CNN)

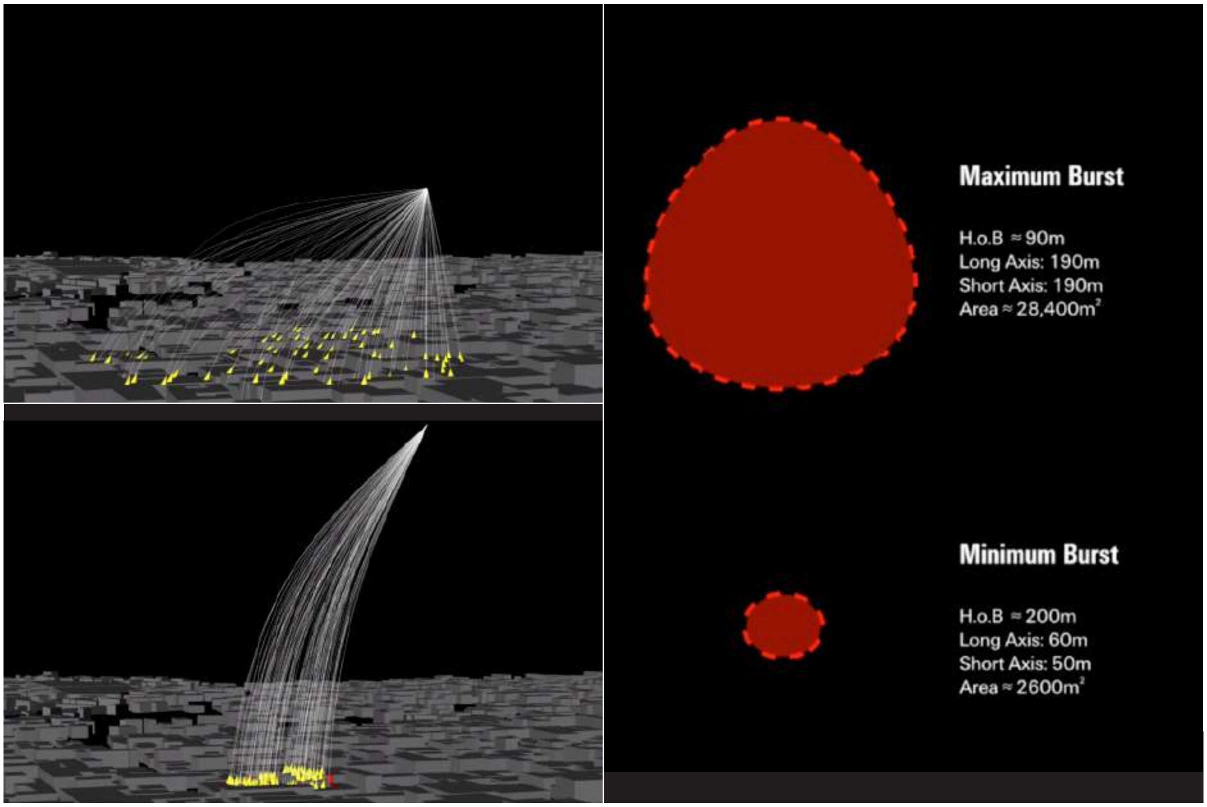



**Figure 14** - 3D simulation: Area Spectrum

## 3.5 Urban Simulation: people and places affected

The analysis is conducted in four typical, densely populated residential neighborhoods, each in a different city: the Jabalya refugee camp, North of Gaza City; the city center of Tel Aviv; the West Village in New York City; and the 9th District of Paris. The cities and sites are chosen arbitrarily and are presented here as examples of a densely populated urban environment. Each of these sites is overlaid with an ellipse delimiting the maximal Coverage Area of the M825 WP projectile.

At this scale of analysis, the distribution of wedges within the Coverage Area itself can be thought of as random: every point in the Coverage Area could potentially be hit by a wedge, so the entire area is considered affected by the WP wedges, and the risk homogeneously distributed within the Coverage Area.

All buildings within the ellipse are considered affected structures: they are identified by land use and counted. Additionally, an estimate is made of the population within the Coverage Area, as an indicator of the total civilian exposure in each scenario.

## 3.3.1 Gaza City


**Figure 15** - Areas examined in Jabalia, Gaza City

### Jabalia Camp

Population: 93,455 people[14]

Area: 1.4 sq miles

Density: 66,754 per sq mile

**Figure 16** - Area A in Jabalia, Gaza City

### Buildings Affected

2 schools

1 pharmacy

2 retail stores

80 housing units

14 Palestinian Central Bureau of Statistics. Population, Housing and Establishment Census 2007 Census Final Results in Gaza Strip - Summary (Population and Housing). Ramallah - Palestine, 2012. 90.

### 3.3.2 Tel Aviv


Figure 17 - Areas examined in the City Center of Tel Aviv

**Tel Aviv City Center**

Population: 7,500 people[15]

Area: 0.18 sq mile

Density: 41,667 per sq mile

Figure 18 - Area F in the City Center of Tel Aviv

**Buildings affected**

500 Housing Units

1 School

2 Museums

30 Local Businesses

15 Israel Central Bureau of Statistics. Summarized File of Localities - Census 2008. Israel, 2010.

### 3.3.3 New York City


**West Village, NYC**

Population: 27,411 people[16]

Area: 0.3 sq mile

Density: 91,370 per sq mile

**Figure 19** - Areas examined in the West Village, New York City

**Buildings affected**

950 Housing Units

40 Local Businesses

1 University Building

1 Church

**Figure 20** - Area G in the West Village, New York City

16 U.S. Census Bureau; Profile of General Population and Housing Characteristics: 2010, 2010 Census Summary File 1. [http://factfinder2.census.gov]

### 3.3.4 Paris

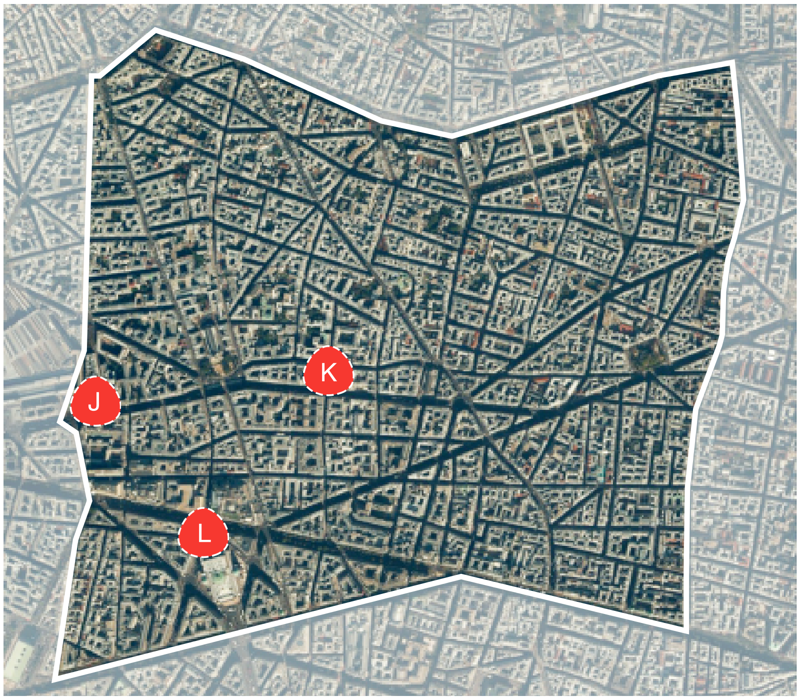



**Figure 21** - Areas examined in the 9th District of Paris

**9th District, Paris**

Population: 61,046 people[17]

Area: 0.84 sq mile

Density: 72,673 per sq mile

**Figure 22** - Area K in the 9th District of Paris

**Buildings Affected**

400 Housing Units

1 Post Office

15 Local Businesses

2 Hotels

17 France. INSEE. Recensement De La Population, Populations Légales En Vigueur à Compter Du 1er Janvier 2012, Arrondissements - Cantons - Communes, 75 - PARIS. 2011.

# 4. Local Effects

## 4.1 Objectives and methods

In this section, the interplay between a single M825 WP round and a given built environment is examined at the scale of a single building.

- Photographic documentation from the ground during an actual WP deployment is studied and the behavior of wedges is examined in relation to a range of architectural features. A series of scenarios are isolated and their anticipated effects described.
- A series of computer-assisted simulations of such deployment are run over a typical urban residential area, in a significant number of iterations. The resulting points of impact of WP wedges are counted and sorted by type of architectural surface impacted. The data thereby assembled is analyzed, and statistical conclusions are drawn about the probability of specific damage scenarios.

## 4.2 Impact analysis

On 17 January 2009, the Jabalya UNRWA school in Gaza was hit by a series of M825 WP rounds.[18] The incident was documented by the Agence France Presse photographer Mohammed Abed. In his series of images, the interaction between the WP wedges and the school complex are captured. These photographs are analyzed here to elucidate a series of scenarios, as well as their potential effects, that may be expected at the scale of an inhabited building.

Based on the photographic analysis, a partial enumeration of the expected scenarios is compiled below:

- **Ricochet**: Traveling at high velocities into the dense matrix of an urban environment, individual wedges can ricochet off their initial impact points and come into contact with other surfaces before coming to rest. Wedges can end up tens of meters from their initial point of impact. The ricochet effect compounds the unpredictable ballistic behavior of the projectile by adding to the effective randomness of the initial points of impact of WP wedges, the ulterior randomness of secondary and tertiary points of impacts. The total Coverage Area can also increase as a result of ricochet effect.

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18 M. Tait /M. Khalili / J. Powell, "'Phosphorus Shells' Hit Gaza Un School". The Guardian [online], 22 january 2009.


**Figure 23** - Ricochet effect: example 1 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)

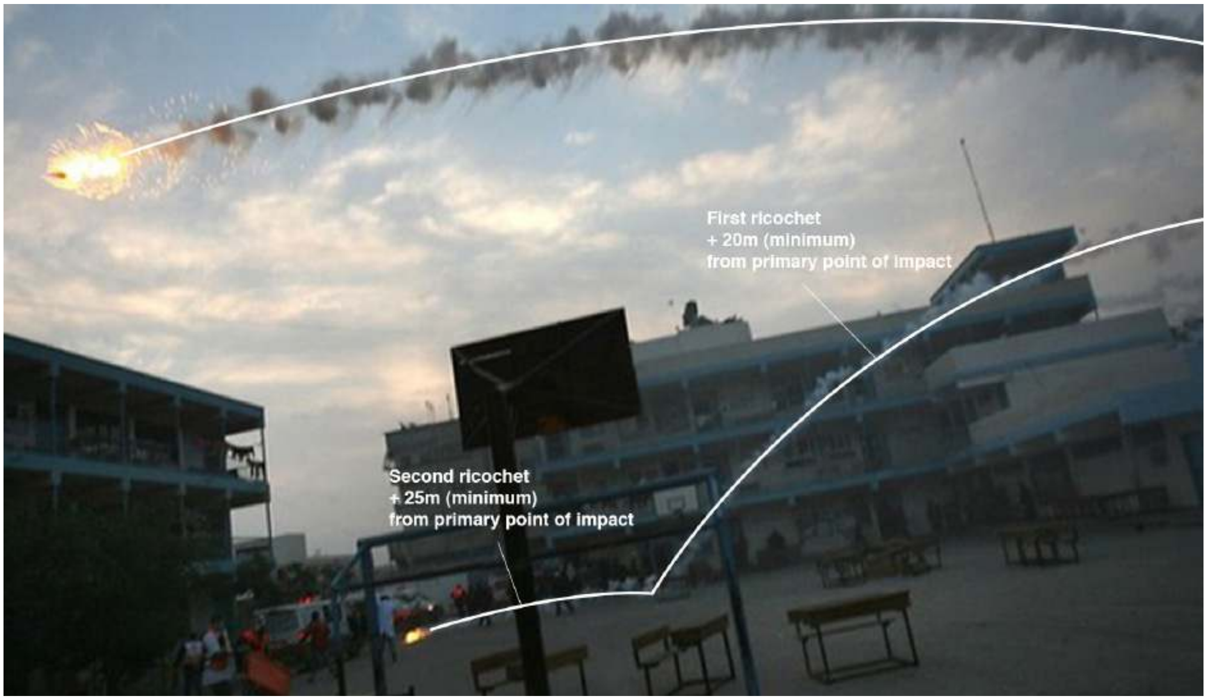



**Figure 24** - Ricochet effect: example 2 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)

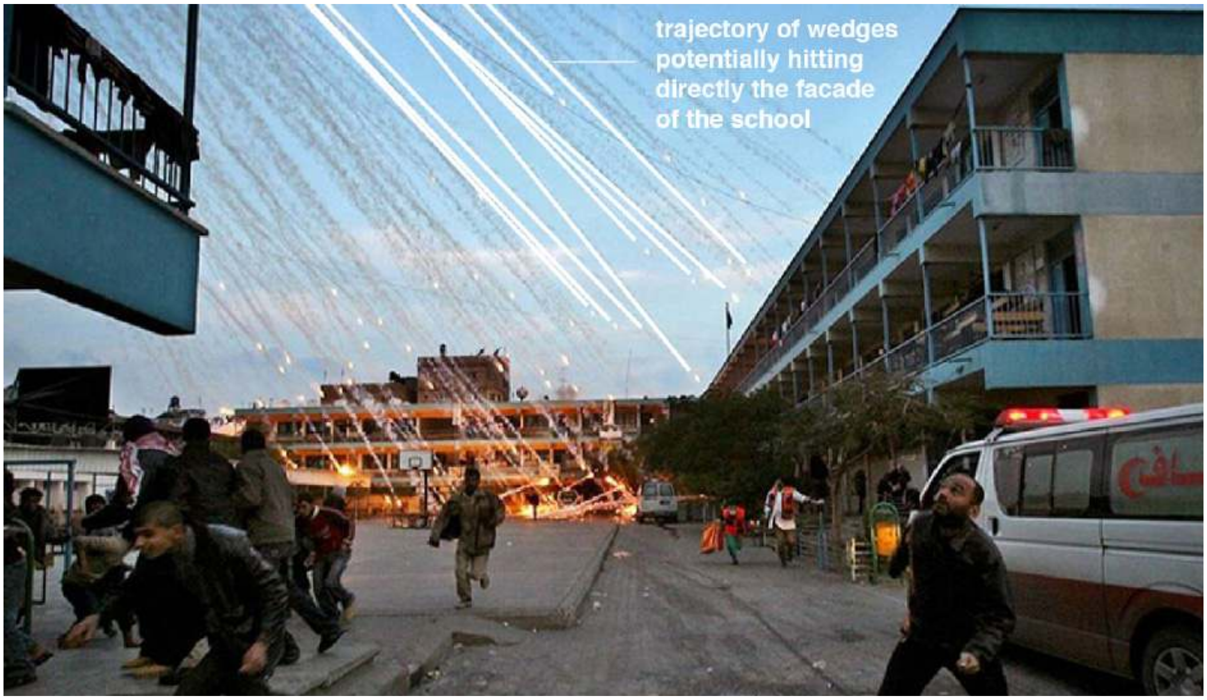



**Figure 25** - Penetration effect: example 1 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)


**Figure 26** - Penetration effect: example 2 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)


**Figure 27** - Ignition/fire effect: example 1 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)


**Figure 28** - Ignition/fire effect: example 2 (Gaza, 17 Jan 2009 - © Mohammed Abed / AFP)

- **Penetration**: Depending on the angle of entry, the wedge can also hit the facade of a building and penetrate through windows into interior spaces or become trapped on an exterior balcony. The concentration of combustible materials in an interior space, if inhabited or used, entails a high probability for a wedge to become an ignition source, and for a fire to break out. Because the combustion of a wedge can only be stopped by cutting off its oxygen supply, fires can be difficult to extinguish.
- **Ignition and fire**: Depending on the type of construction the wedge can either burn or emit smoke until complete consumption of WP occurs or, if in contact with combustible materials such as wood, straw or plastic, can function as an ignition source and set the surroundings on fire.

## 4.3 Architectural simulation

The parametric model of a M825 WP round is here employed in order to simulate the trajectory of single WP wedges, and their interaction with architectural features in a typical residential urban environment — in this case, the Jabalya refugee camp.

In the model, a script is run to randomize the initial distribution of WP wedges at burst, so as to reproduce the random dimension of their distribution in real deployment. From this moment of random burst, the fall trajectory of each wedge in the air is simulated according to its speed, weight and shape. The model is set to register the initial points of impact of the WP wedges, to count and to classify them according to the type of surface impacted – either roof, facade, or ground. Only initial points of impact are considered here, and the model does not attempt to simulate ricochet effects.

150 iterations of the simulation were run over a 30,000 square meters area of Jabalya. The results have been recorded and analyzed, in order to assess the statistical probability of each impact scenario.

Based on 150 iterations of the computer-assisted simulation with the selected parameters, we find the following:

- 149/150 = 99% probability that at least 60 wedges hit roofs
- 139/150 = 93% probability that at least 20 wedges hit a facade
- 147/150 = 98% probability that at least 15 wedges hit the ground

*Note: the results of this analysis are best viewed on the online version of this report (http://www.forensic-architecture.org/WhitePhosphorus/?pageid=13 )*

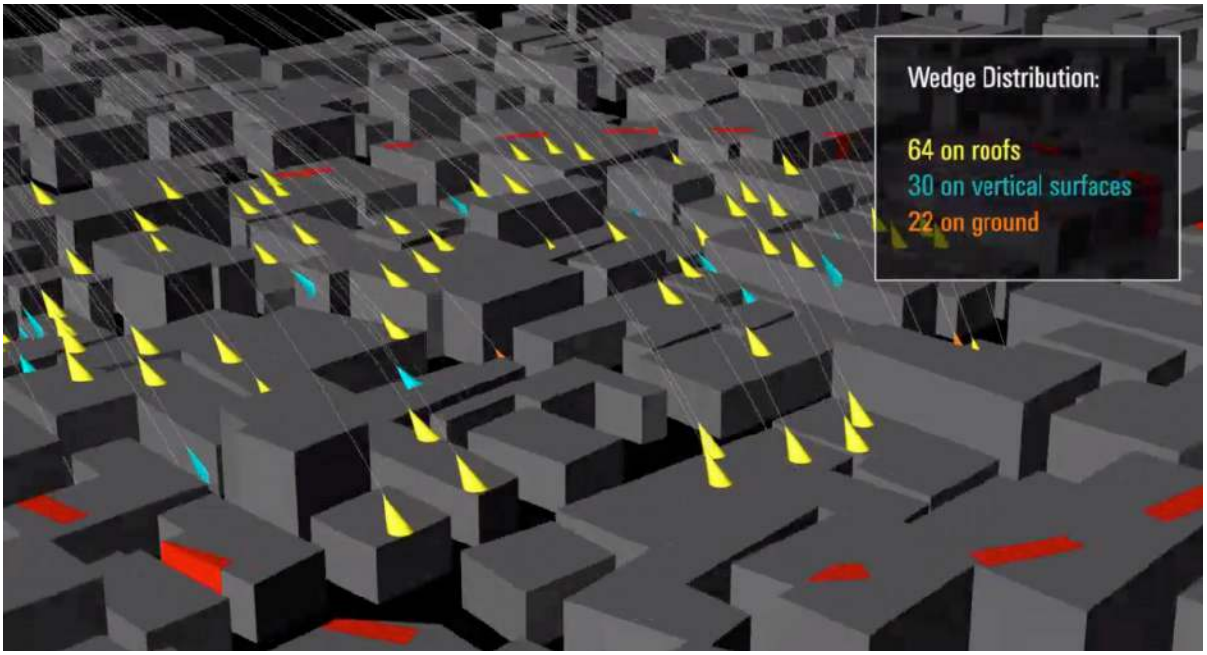



**Figure 29** - Still from the computer-assisted architectural simulation

# 5. Conclusion

The deployment of the M825 WP projectile in Fallujah (2004) and Gaza (2009) makes them relevant case studies for the analysis of the effects of air-burst white phosphorus munitions in urban environments, as conducted throughout this report.

An M825 WP round will distribute its payload of 116 burning WP wedges within an elliptical perimeter, whose area is between 5,000 and 30,000 m2, depending on how the round has been fired. This Coverage Area can therefore be larger than a whole Manhattan block. In a city of comparable density to New York or Gaza, it corresponds to the area inhabited on average by 50-300 people, and by over a 1,000 people in specifically dense zones.

There are numerous variables that influence the trajectory of each single WP wedge. The precise point of burst of the projectile in the air, the initial distribution of the wedges at burst, the meteorological conditions, the type of surface first impacted in the urban fabric, the potential for a ricochet effect, as well as others. Most of these variables are not under the control of the armed forces deploying the M825 WP projectile. Therefore:

- The exact distribution and trajectory of each WP wedge must be considered random.
- Any surface, object or person situated directly under the burst of a M825 WP round is at risk of being hit by a WP wedge.

The diversity and density of structures and objects that is characteristic of any urban environment must be taken into account when evaluating the incendiary effect that can be expected when white phosphorus munitions are to be deployed within urban contexts. The chances for burning white phosphorus to react with various combustible materials present in the urban fabric, and therefore to function as an ignition source, are largely increased compared to a deployment in open battlefield. Moreover, the fires that may consequently break out can affect a large number of civilian persons and objects.

**For all the above reasons, and regardless of the primary motivation for the military use of airburst white phosphorus munitions, their deployment in urban environments puts the civilian population in these areas at great risk of death or injury, and the civilian objects and environment at an equal risk of destruction, damage, or contamination by a flammable and toxic substance. This risk cannot be managed nor controlled by the armed forces that deploy these munitions.**

# ANNEX A:
# Felt Wedges Specifications

White phosphorus wedges specifications were arrived at by cross-referencing various United States Department of Defense documents.[19] [20]

**i.**

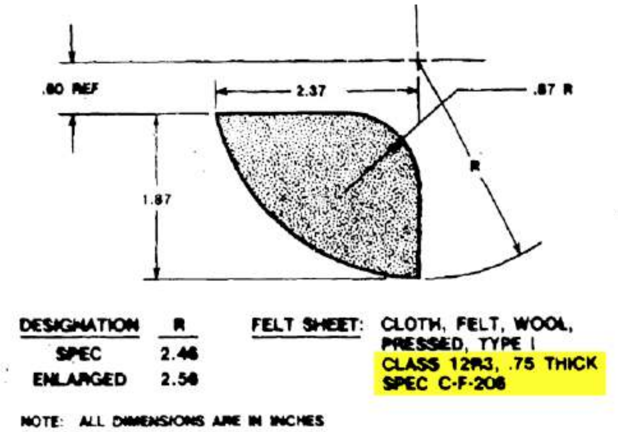
TABLE I. Chemical and physical requirements for type I felts (cont'd)

| Classification number | Corresponding S.A.E. felt number 1/ and trade designation | Wool fiber content 2/ (min) percent | Soluble matter percent: 1,1,1-trichloroethane (max) | Soluble matter percent: Water (max) | Soluble matter percent: Total (max) | Ash content (max) percent | Tensile strength (min) p.s.i. 3/ | Splitting resistance (min) lb per 2 inches of width 3/ | Width (min) inches | Color | Thickness, inches: Nominal | Thickness, inches: Min | Thickness, inches: Max | Weight, lb per sq yd: Min | Weight, lb per sq yd: Max |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 1/8 | 0.111 | 0.139 | 1.45 | 1.61 |
| | | | | | | | | | | | 3/16 | 0.172 | 0.204 | 2.17 | 2.41 |
| | | | | | | | | | | | 1/4 | 0.232 | 0.268 | 2.90 | 3.22 |
| | | | | | | | | | | | 5/16 | 0.293 | 0.333 | 3.62 | 4.02 |
| | | | | | | | | | | | 3/8 | 0.353 | 0.397 | 4.35 | 4.83 |
| 12R1 | F-5 | 95 | 2.5 | 2.5 | 3.0 | 2.0 | 400 | 18 | 60 | White | 1/2 | 0.474 | 0.526 | 5.80 | 6.80 |
| | | | | | | | | | or 72 | | 5/8 | 0.595 | 0.655 | 7.25 | 8.05 |
| 12R2 | F-6 | 87 | 2.5 | 2.5 | 4.5 | 2.5 | 275 | 16 | 60 | Gray | 3/4 | 0.716 | 0.784 | 8.70 | 9.66 |
| | | | | | | | | | or 72 | | 7/8 | 0.837 | 0.913 | 10.15 | 11.27 |
| 12R3 | F-7 Extra firm pad | 80 | 4.0 | 4.0 | 7.0 | 3.0 | 250 | 12 | 72 | Gray | 1 | 0.958 | 1.042 | 11.60 | 12.88 |

19 Miller, Miles C., and Daniel D. Joseph. Proceedings of the Workshop on Problems of Rotating Liquids Held in Minneapolis, Minnesota on 22-23 April 1991. Ft. Belvoir: Defense Technical Information Center, 1991. 259.

20 "C-F-206G, Federal Specification: Felt Sheet: Cloth, Felt, Wool, Pressed (20 Jun 1989) [Superseding MIL-F-5656A]."

**ii.**




**iii.**

**Wedge area:** 3.065 sq. in

**Wedge thickness:** .75 in

**Translation between specified felt weight and wedge:** 12.84 g

**Weight of Phosphorus:** 49.7 g

**Total weight:** 12.8 + 49.7 = 62.5 g

As seen from the front, the projectile has a silhouette area of .003167 m2

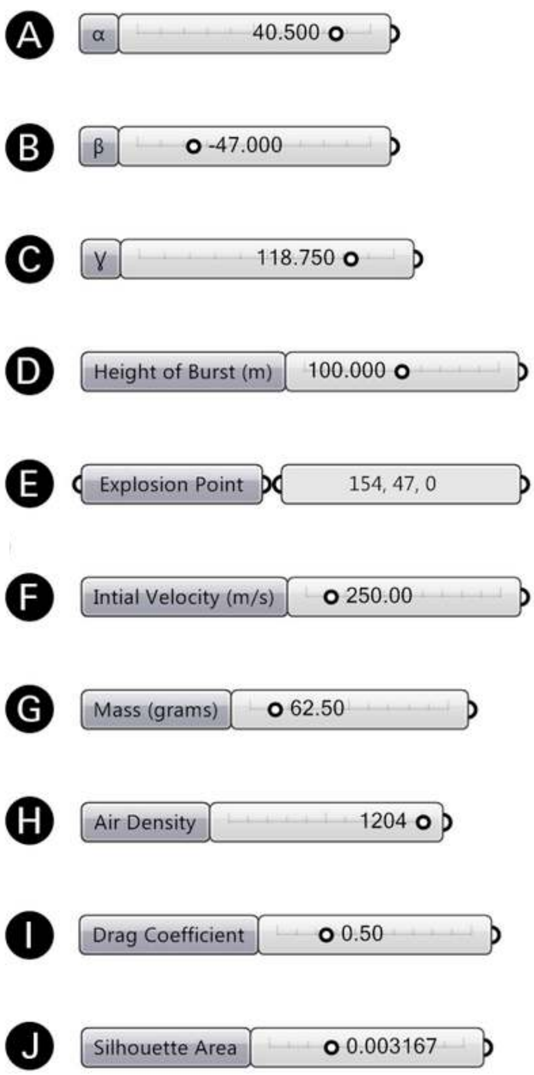
## iv. Assumptions

| | |
|---|---|
| White Phosphorus Felt Wedge Mass | 62.5 g |
| Initial Wedge Velocity | 250 - 500 m/s |
| Air Density | 1204 $g/m^3$ |
| Drag Coefficent | .5 |
| Silhouette Area | .003167 $m^2$ |

# ANNEX B:
# Parametric Modeling

The flight path of the white phosphorus wedges after burst of the M825 WP projectile was modeled using parametric software as outlined below. Items **v** and **vi** outline projectile motion functions while **vii** and **vii** outline randomization functions used for modeling wedge dispersion.

**v.**




Variables used in the definition. Alpha, beta, gamma and height of burst (A, B, C, and D, respectively) are determined by footage analysis.

The explosion point represents a point drawn on the ground plane (E).

Initial velocity (F) comes from US Army field manuals.

The mass of each felt wedge is plugged in (G).

Air density (H) assumes temperature between 20 and 30 degrees Celsius while the drag coefficent (I) is based on that of a flat plate.

Sillhouette area (J) of each felt wedge is also included.

### vi.

The distance traveled (d) of a projectile over a given period of time (dt) is dependent on its:

launch angle (A)

initial velocity (V)

Initial velocity is split into its vertical and horizontal components (Vx,Vz) based on the launch angle. Each is calculated independently:

Vx = V * cos(A)

Vz = V * sin(A)

The distance traveled (dx,dy) over a given interval of time (dt) is based its velocity (Vx,Vz) and its acceleration (Ax,Az). Each direction is calculated independently:

d x = Vx * dt +0.5 * Ax * dt

d z = Vz * dt +0.5 * Az * dt2

For a realistic path we must take into account air resistance. Acceleration due to air resistance at any time is dependent on velocity (V), drag (D), and mass (m).Component velocity is incorporated to correct for current angle:

Ax = -(D/m) * V * Vx

Az = -g - V * Vz

```
Sub RunScript
        (
                ByVal A As Double, R
                ByVal V As Double,
                ByVal dt As Double,
                ByVal D As Double,
                ByVal m As Double,
                ByVal T As Double,
                ByVal X As Double,
                ByVal Z As Double
        )

Dim dblX As New List(Of Double)
Dim dblZ As New List(Of Double)
Dim dblVx As Double
Dim dblVz As Double
Dim dblAx As Double
Dim dblAz As Double

dblVx = V * math.cos(A)
dblVz = V * math.sin(A)

Dim i As int32

dblX.Add(x)
dblZ.Add(z)

For i = 0 To T

dblAx = -1 * (D / m) * dblVx * V
dblAz = -9.8 - (D / m) * dblVz * V

dblVx = dblVx + (dblAx * dt)
dblVz = dblVz + (dblAz * dt)

V = math.sqrt((dblVx * dblVx) + (dblVz *
dblVz))

x = x + ((dblVx * dt) + (.5 * dblAx * dt * dt))
z = z + ((dblVz * dt) + (.5 * dblAz * dt * dt))

dblX.Add(x)
dblZ.Add(z)

Next

_x = dblX
_z = dblZ

End Sub
```

A = launch angle
V = initial velocity
dt = change in time
D = drag
m = mass of canister
T = total time (limit)
X = initial position of canister
Z = initial position of canister

Declare all equation variables:
Split velocity into component Vx and Vz for x and z directions.
Split acceleration into component Ax and Az for x and z directions.

Set Vx equal to Vi * cos(A).
Set Vz equal to Vi * sin(A).

Begin time loop, adding acceleration due to drag and gravity, calculating a new velocity for each time Step, locating new point (x, z) along trajectory curve.

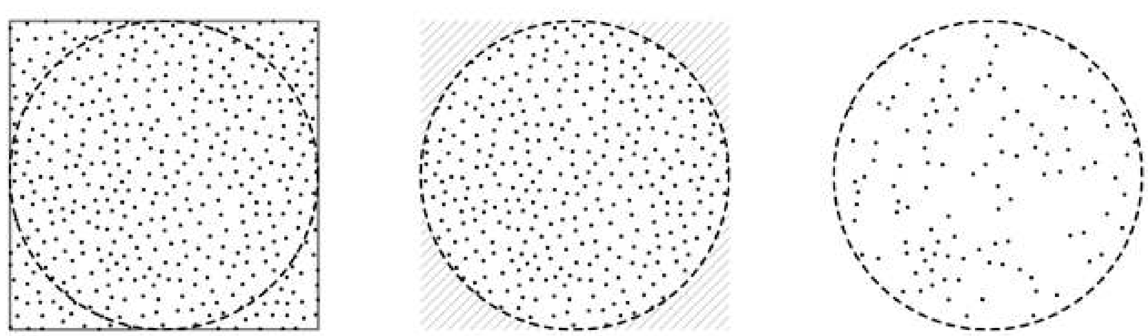
Drag is pre-calculated using the density of the medium through which the projectile is traveling (p), the object's coefficient of drag (C), and the silhouette area (A) of the projectile:

D = (p * C * A) / 2

Because the velocity of the projectile is continuously affected by external forces, at each instant in time it has a slightly modified velocity and therefore acceleration.

For this reason, the projectile's path must be iteratively calculated with sufficiently short time steps, or intervals updating acceleration, velocity, and position. For an accurate projectile path, and because many calculations must be performed to produce the new input variables for each time interval, a computer script was written in order to loop through the large number of calculations necessary.

**vii.**



Left to right:

After taking a slice through an idealized cone at one meter from the the point of burst, a square is circumscribed around the filter and then populated with 450 randomly placed points; all points that are not located within the filter are removed; the remaining points are randomly culled until only 116 are left. A vector is drawn from the point of burst to each point, thereby defining initial direction for each wedge. Each wedge is then treated as an individual entity andpushed through the model that iteratively calculates projectile motion.

**viii.**

**Visual Basic Random Function**

A linear-congruential method for pseudo-random number generation.[21] This method takes the form of:

xn+1 = (axn+c) (mod m)

where:

**xn+1** is the new value

**xn** is the previous value or seed

**a** is a constant with the value 1140671485

**c** is a constant with the value 12820163

**m** is a constant with the value of 224

The Visual Basic Random Function produces a floating point number between 0.0 and 1.0.

21 "How Visual Basic Generates Pseudo-Random Numbers for the RND Function." Microsoft. [online] http://support.microsoft.com/kb/231847/

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