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Reverse Engineering The Type Of Warhead(s) That May Have
Destroyed The Mariupol Theatre

University of Wales Trinity Saint David
Scientific Principles of OME Design ACDB 6008

Ordnance, Munitions and Explosives Degree Apprenticeship
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Executive Summary

In response to a request issued by the International Criminal Court (ICC), this report presents a technical assessment of the ordnance most likely employed in the attack on the Donetsk Regional Academic Drama Theatre in Mariupol, Ukraine, on 16th March 2022. The assessment was conducted through analysis of blast effects, structural damage, and comparative ordnance characteristics of the weapon system most consistent with the observed damage. Due to the absence of physical access to the site, demolition of the structure and subsequent Russian occupation, the analysis is based on satellite imagery, open-source reporting, and established blast and structural engineering principles.

The Kingery-Bulmash framework was employed to establish conservative free-field baseline pressure and Net Explosive Quantity (NEQ) requirements. Concluding a NEQ of 173-179kg of TNT was required to produce the 10psi pressure to cause significant damage to building structures. This would be reduced to 48-50kg when considering reflected blast waves.

A comparative ordnance analysis was undertaken to evaluate candidate weapon systems based on explosive yield, fuze behaviour, delivery feasibility and platform consideration as well as consistency with the damage observed.

Analysis of satellite imagery and damage patterns indicate that the munition penetrated the roof above the performance space and detonated internally. The resulting outward displacement of debris, catastrophic collapse of the roof structure, and comparatively limited damage to the front portion of the building are consistent with internal detonation within a confined or semi-confined environment. These characteristics are not consistent with external surface detonations, ground blast effect, or fragmentation-dominated weapon systems.

Comparative ordnance assessment excluded missile, rocket, Fuel-Air, fragmentation and submunition based systems. Medium-weight aerial bombs within the 500kg class were assessed as technically credible. Given the accuracy required to achieve a centrally located internal detonation, alongside limited collateral damage, evidence and analysis indicates the use of a guided munition.

On this basis, the KAB-500-S-E was identified as the most likely weapon used in the attack. While uncertainties remain due to data limitations, the findings provide a technically robust assessment.

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1 Introduction

In response to a request issued by the International Criminal Court (ICC), an investigation has been undertaken to determine the ordnance most likely employed in the attack on the Donetsk Regional Academic Drama Theatre (Mariupol Drama Theatre) on 16th March 2022. The attack occurred within the opening months of the Russia-Ukraine War during which the theatre was one of a number of civilian shelters in the besieged city of Mariupol [1, 2, 3].

The assessment was conducted using the established technical benchmark of 10psi (approximately 68.95kPa) as the overpressure required to initiate structural failure. A multi-disciplinary approach was applied consisting of site and contextual analysis, application of scientific principles governing blast-structure interaction and execution of technical blast-effect calculations. A comparative assessment of candidate ordnance types, cross referencing Russian aviation platforms used in the region, was also undertaken.

2 Site Analysis: Mariupol Drama Theatre

2.1 Location and Context

The Mariupol Drama Theatre (Figure 2-1) was situated on the Central Square in Mariupol, located in the Donetsk Oblast of Ukraine [4]. As a cultural centre and the only professional theatre in Mariupol, it was built in an open area surrounded by a public park. As shown in the map in Figure 2-2, it was in an isolated location, with no significant buildings within a 100m radius.



Figure 2-1 - Mariupol Drama Theatre Before 16th March 2022 [4]

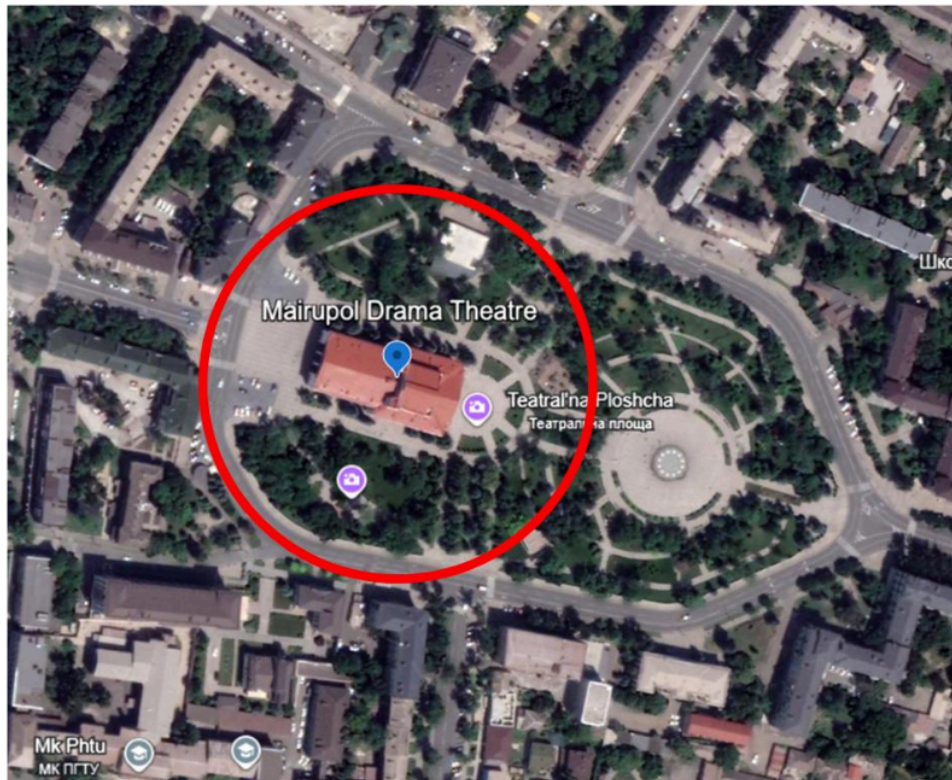


Figure 2-2 - Satellite Imagery of Mariupol Drama Theatre Location, Highlighting 100m Radius Around the Central Point of the Building. Image from Google Earth, Historical View from 21st June 2021 [5]

2.2 Dimensions and Construction

The exact construction of the theatre is currently unknown; however, the theatre was originally built around 1956-1960 [4] and has been described as “a stone building with white pillars, a classical frieze, and a distinctive red roof” [6]. It would have been initially constructed according to standardised architectural design for culturally significant buildings [7, 8], marking it as a typical example of contemporary Soviet theatres in the region as shown in Figure 2-3.



Figure 2-3 - Four Ukrainian Theatres Built According to One Typical Project by O. O. Krylova and O. O. Malysenko 1952-1958. ©Center for Spatial Technologies [7]

Based on standardised 1950s Soviet construction practices, the theatre can be characterised as a typical reinforced masonry structure. Massive 1m thick load-bearing walls [6] and poured concrete floors were incorporated into its design [1, 8] As presented in Figure 2-4, the theatre had four floors and a basement, with the layout consisting of internal structures and a large, open performance hall to the rear. The roof above the performance space is thought to have incorporated steel girders and decking [8, 9]. This configuration is consistent with the broadening Soviet transition at the time toward reinforced concrete-frames in support of expansive internal spaces. The intent of this design change was to balance monumental architectural expression with the efficiency of industrialised construction methods [8].

Table 2-1 provides key measurements of the structure obtained from detailed floor plans [7].

Table 2-1 - Structural Dimensions of the Mariupol Drama Theatre

Height (At Highest Height)	21.96 m
Width (Performance area)	36.78 m
Width (Entrance)	28.78 m
Length	68.17 m

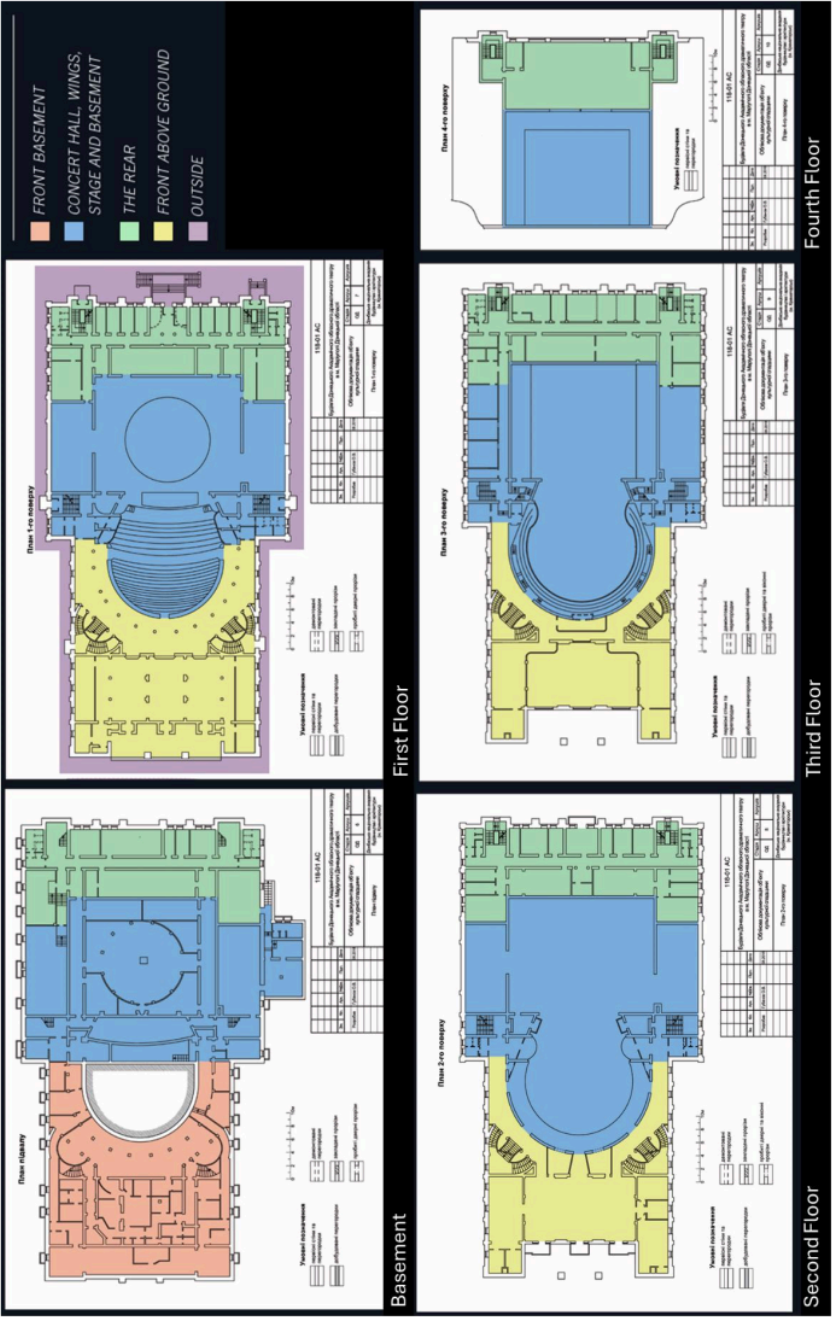


Figure 2-4 - Schematics of the Internal Layout of the Mariupol Drama Theatre, Provided from [1]

3 Analysis of The Attack on The Mariupol Drama Theatre

On 16th March 2022, at approximately 10am, an explosion caused significant damage to the Mariupol Drama Theatre. At the time of the strike the theatre was being used as a humanitarian hub and public shelter, housing an estimated 1,000 civilians [2, 6, 7]. Figure 3-1 shows the theatre prior to the attack with “CHILDREN” (“ДЕТИ”) painted in large in Russian on the ground at both front and rear entrances. This was to easily identify its humanitarian use from the air. Reports and witness testimonies consistently state there was no military presence inside or near the building [1, 6, 7].

Witness accounts from the attack describe hearing a plane followed by a “high-pitched whistle” or the sound of an explosion [1, 6, 7, 10, 11]. 87% of the witness statements recall one audible explosion with 13% recalling two explosions in rapid succession [9]. This disparity is not unusual as high levels of stress can affect the overall accuracy of witness statements following a traumatic event [12].

Figure 3-2 shows the subsequent damage to the theatre. In December 2022, whilst under Russian occupation, the ruins of the theatre were entirely demolished [2, 7], preventing a full forensic site analysis.



Figure 3-1 - Satellite Imagery of the Mariupol Drama Theatre from 14th March 2022, Highlighting the Performance Space, Field Kitchen and "CHILDREN" Marked on the Ground. Image provided from [1]



(a)



(b)



(c)

Figure 3-2 - Mariupol Drama Theatre Post Strike from a) The Front, b) The Rear and c) The Side of The Building

3.1 Mariupol Drama Theatre Destruction Analysis

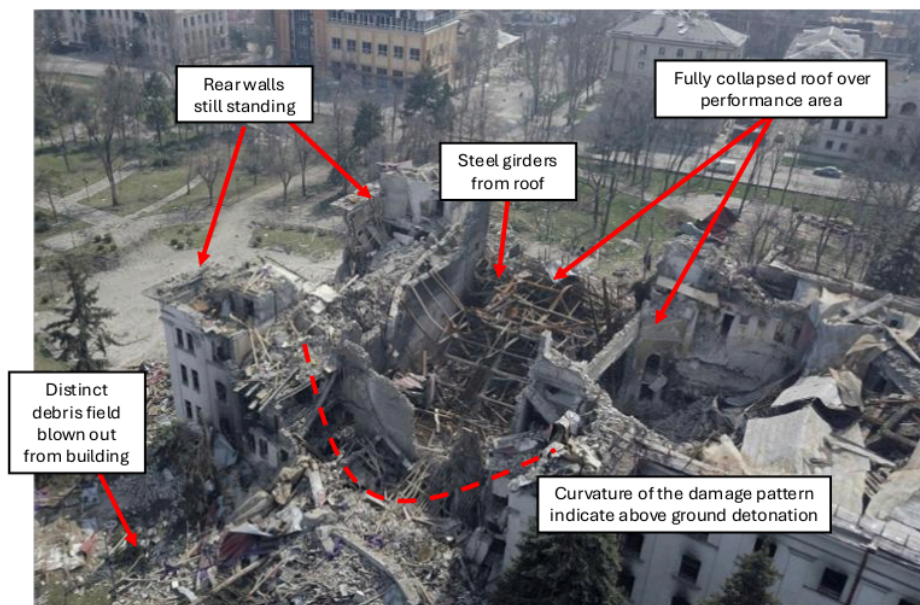
Analysis of satellite imagery and physical damage (Figure 3-3-Figure 3-5), indicates the ordnance entered through the roof of the performance area and detonated inside the building. This combined with the reported presence of an aircraft implies the use of an **air-to-surface munition**. The lack of crater and significant fire damage suggests the use of a **high explosive air burst munition**, configured to detonate either at a set time after the initial impact or distance above the ground. If multiple munitions were used, they would have been released and detonated in close proximity to each other.



Figure 3-3 - Internal Destruction of Mariupol Drama Theatre [6] Highlighting Blast Damage and Lack of Significant Fire Damage

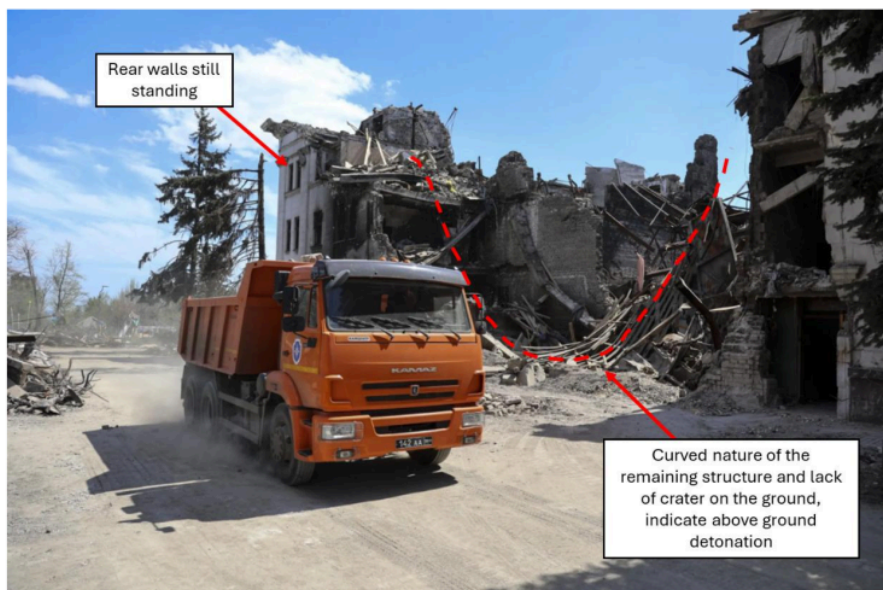


(a)



(b)

Figure 3-4 - Destruction of Mariupol Drama Theatre from a) The Rear, b) The Side, Highlighting Collapsed Roof and Evidence of Internal Detonation



(a)



(b)

Figure 3-5 - External Debris of Mariupol Drama Theatre [6] Highlighting Evidence of Internal Blast

The subsequent blast destroyed interior walls and breached the exterior load-bearing side walls, creating two distinct debris fields on the north-eastern and south-western sides, highlighted in Figure 3-6. Figure 3-2 - Figure 3-6Figure 3-2 show that while the roof over the performance area collapsed entirely, the front portion of the building remained relatively intact.

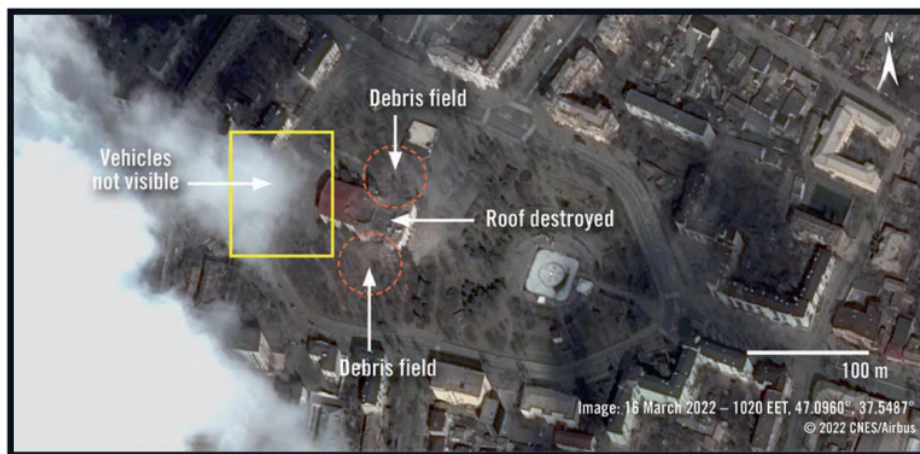


Figure 3-6 - Satellite Imagery of The Mariupol Drama Theatre from 16th March 2022, 1020 EET, Showing The Destruction of The Roof Above The Performance Space and Highlighting The Two Debris Fields. Image Provided From [1]

4 Internal Blast Interaction with Structures

To fully evaluate the potential munition used in the Mariupol Drama Theatre attack, the interaction of blast waves internal to a structure needs to be understood.

Detonating an explosive within a confined or semi-confined structure adds complexity to blast wave propagation. External blast wave theory focuses on a single blast wave propagating through an unbounded medium, while internal blast theory considers confinement and reflections, fundamentally altering the load profile and destructive potential [13, 14, 15].

Internal detonation subjects a structure to three distinct loading components:

- **Initial Shock Pressure** – The primary supersonic wave that strikes the nearest surfaces [14, 16], however, due to the element of confinement, this initial wave does not dissipate into the atmosphere [17].
- **Multiple Reflections** – As shock waves strike internal walls, floors and ceilings, they are reinforced and reflected [13, 14]. These waves interfere with one another creating a multi-peak overpressure curve, where subsequent reflections can exceed the initial peak pressure [17, 18]. This may also generate multiple Mach Stems, where the reflected waves merge with the incident wave forming a combined wave [19]. In confined spaces, reflected pressures are typically 2 to 11 times higher than those of a free-field explosion of the same charge weight [18].
- **Gas Pressure** – This is an element that is not considered for external blasts [16]. High temperature gas is a typical byproduct of an explosion. In an internal explosion, these gaseous products accumulate within the structure [14]. This quasi-static gas pressure has a much lower peak value than the initial shock wave, but a significantly longer duration. This build up can add to the impulse exerted onto the structure, often lasting until the gases are vented through structural failure or openings [14, 17].

In internal spaces, the destructive energy is further amplified by afterburning [17]. Many high explosives, such as TNT, are oxygen-deficient meaning that during

the aerobic stage of detonation, unreacted fuel particles from the explosion mix with the oxygen trapped inside the room and ignite [17, 20]. Research indicates that afterburning can amplify initial peak overpressure by 1.79 times and quasi-static pressure by 2.21 times, increasing total structure deflection by over 170% [17].

The utilisation of frangible elements designed to fail quickly, such as windows or light roof decking, provide ventilation allowing the shock waves and gasses to dissipate into the atmosphere [14, 15, 18].

4.1 Structure Failure from Blast Waves

An external blast, with a time duration of milliseconds, causes an “implosive” effect, pushing walls into a building. The overpressure from an internal blast blows the outer structure out and away from a buildings centre [16, 21] as seen in the Mariupol Theatre debris fields.

The duration of the gas pressure stage is critical for an internal blast [14]. If the gas pressure persists for a long duration, it can often exceed the Natural Period of a structure [13]. The Natural Period is the time taken for a building to oscillate after being disturbed by a wave [22]. The long-duration load prevents the structure from rebounding and shifts the loading regime from impulsive, sensitive to total energy, towards quasi-static, sensitive to peak force [13, 14, 20]. If the buildings Natural Period is exceeded by this duration, failure is most certain [13, 14, 23], consequently, structures that might survive a millisecond long external pulse will fail under sustained internal pressure of a confined blast [14, 17].

The Mariupol Theatre was constructed primarily from thick load-bearing masonry walls, a structural form characterised by high compressive capacity but limited tensile strength. Under internal blast loading, the structure would have been subjected to predominantly outward-acting tensile stresses generated by the blast wave and the subsequent accumulation of quasi-static gas pressure. As masonry structures are inherently resistant to tensile and flexural demand, these loading conditions would have exceeded the material's structural capacity, leading to progressive cracking, wall separation and ultimately failure.

4.2 Effects of Ventilation during the Mariupol Drama Theatre Strike

The damage to the Mariupol Theatre was caused by internal blast, and while the hole in the roof caused by the munitions ingress to the building would have provided an element of ventilation, the effects would have been negligible during the initial stages. The impact of ventilation is determined by the scaled venting ratio [14]:

$$\text{Scaled Venting Ratio} = \frac{A}{V^{\frac{2}{3}}} \quad 4-1$$

Where A is the area of the opening and V is the volume of the space. The ordnance likely used in the strike would cause a hole no larger than 1m^2 , this is based on approximate sizing of probable munitions discussed in Section 6 - Comparative Ordnance Analysis. The volume of the performance area (blue section in Figure 2-4) is approximately $14,250\text{m}^3$, resulting in a scaled venting ratio of 0.0017. Technical standards define small venting areas as those where the ratio is ≤ 0.022 [14], the ratio for the theatre is nearly 13 times smaller than the threshold placing it closer to a fully confined environment. Venting and dissipation of the blast effects would eventually occur after structural failure of the building.

5 Technical Calculations

To determine the likely ordnance used in the Mariupol Theatre attack, an understanding of the probable Net Explosive Quantity (NEQ) is required. This was evaluated using technical calculations based on the required pressure to cause significant damage or to destroy a structure.

For the analysis, a benchmark overpressure of 10psi (68.95kPa) has been determined as the minimum threshold to destroy the structure. Standard literature corroborates this value, with multiple sources describing the effects from an overpressure of 10psi (68.95kPa) to be the probable destruction of a building [24, 25, 26] and for reinforced concrete structures to be severely damaged or destroyed [23].

Due to the complexity of internal blast analysis, it is worth considering that the required overpressure may have been a result of reflected pressure rather than incident pressure.

5.1 Overpressure Derivation

Kingery-Bulmash [27] provides authoritative semi-empirical formulas which are widely established to determine free-field blast parameters such as incident overpressure (P_{so}), reflected pressure (P_r), and impulse. They are standardised for TNT-equivalency, enabling the conversion of different explosive compositions into a universal equivalent.

The framework utilises the Hopkinson-Cranz scaling law [13], which correlates the distance from a detonation to the size of the explosive charge, this is known as the scaled distance. Scaled distance is defined as:

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad 5-1$$

Where Z is the scaled distance in $mkg^{-\frac{1}{3}}$, R is the distance from the centre of the detonation in meters (m), W is the NEQ of the explosive charge in kg .

Kingery-Bulmash applies this relationship through polynomial functions and graphical curves (Figure 5-1) where Z is the independent variable.

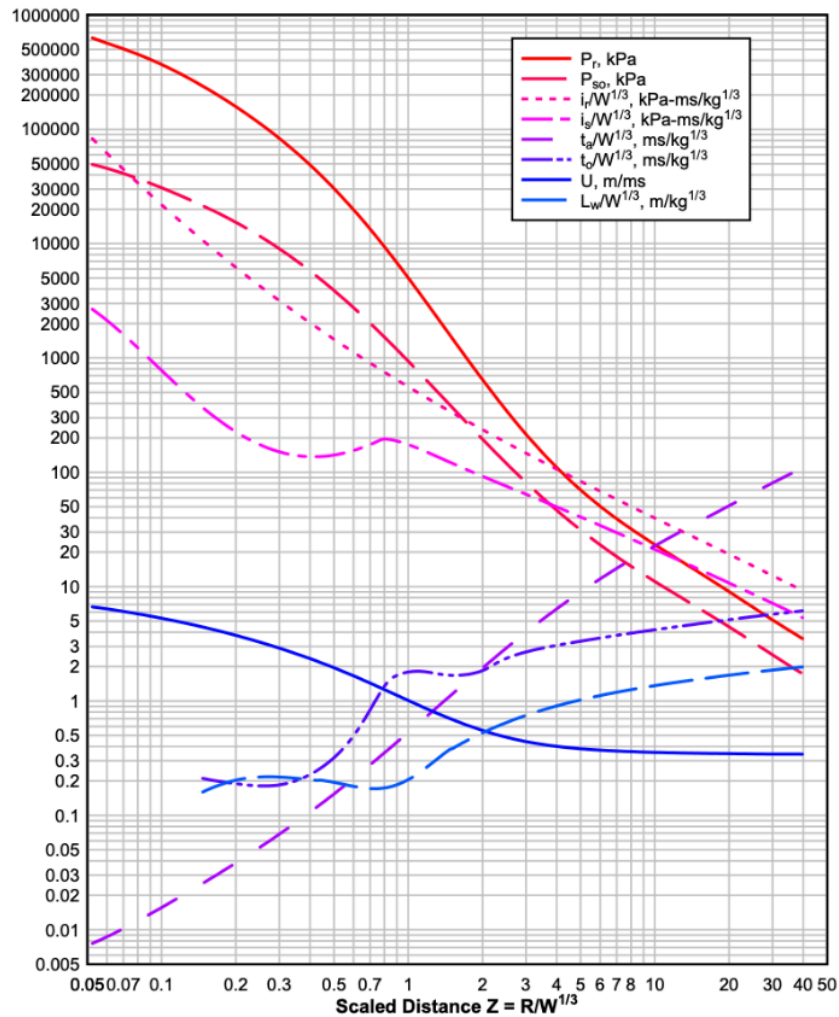


Figure 5-1 - Kingery-Bulmash Curves for Blast Parameters During the Positive Phase from Free Field Air Burst of a Spherical Charge of TNT [13]

Although the Kingery-Bulmash methodology is derived from free-field air-burst conditions without structural interaction, it provides a baseline for the Mariupol Theatre analysis. Internal detonations deviate from the free-field assumptions and blast theory literature demonstrates that Hopkinson-Cranz scaling laws

remain suitable for incident and reflected pressure where post-detonation confinement effects are uncertain or unverifiable due to the absence of forensic site access [13].

5.2 NEQ Determination

Based on the analysis of the debris at the side of the theatre, it can be deduced that the blast originated approximately at the centre of the performance area shown in Figure 5-2.

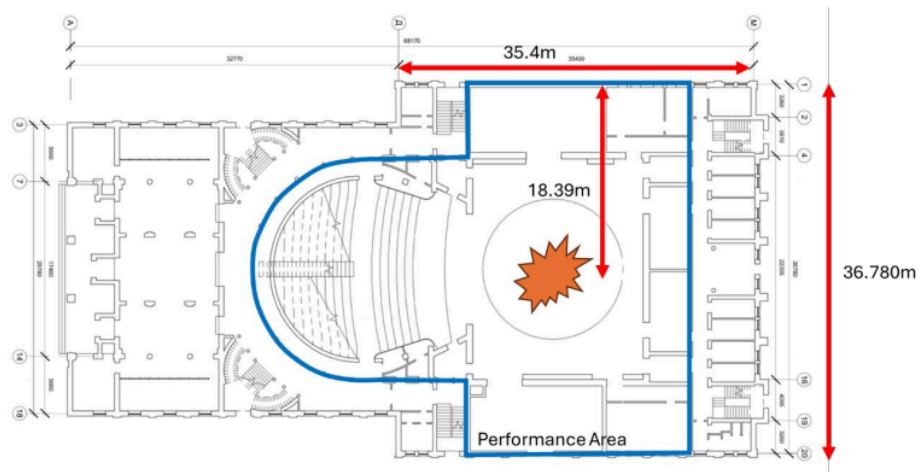


Figure 5-2 - Detonation Point for Kingery-Bulmash Blast Calculations

Due to the complexity of accurately determining the scaled distances based on the calculations conducted in 9Appendix A, to achieve the required incident overpressure of 10psi (68.95kPa) sufficient to destroy walls at 18.39m (which is a scaled distance of $3.26\text{-}3.3\text{mkg}^{-\frac{1}{3}}$) an NEQ of 173-179kg of TNT is required. For a reflected pressure of 10psi (68.95kPa) the NEQ decreases to 48-50kg of TNT.

6 Comparative Ordnance Analysis

6.1 Delivery Platform Consideration

In accordance with the scope defined by the ICC, the focus of this evaluation considers the Russian Flanker aircraft as the potential delivery platform, due to their documented deployment during the early phase of the Russian-Ukraine conflict [28, 29, 30]. Flanker is the NATO reporting name for the Su-27, a long-range, highly manoeuvrable air superiority fighter that serves as the baseline airframe for a series of aircraft with air-to-surface strike capability [31]. The Flanker family encompasses the Su-30 (Flanker C), Su-32, Su-33 (Flanker D) and Su-35S (Flanker-M) variants, each adapted for specific operational roles while retaining broadly comparable air-to-surface weapon capability. Consideration is also given to the Su-34 (Fullback), a multirole fighter-bomber derived from the Su-32. The Su-34 has been reported as operationally active in the strikes during Russia's campaign for air superiority and ground attack missions in Ukraine [28, 29, 30].

Due to their ground fighting capabilities and reported presence in the conflict, the Su-30 (Flanker C) and Su-34 are the most probable aircraft used during the strike. Their weapon system capability is shown in Table 6-1 [30, 32, 33].

Table 6-1 - Su-34 and Su-30 Weapon System Capability

	<i>Su-34 Fullback</i>	<i>Su-30 Flanker C</i>
<i>Air-to-Surface Missile Weapon System</i>	Kh-29T/L/D	Kh-29T/L
	Kh-38MAE/MKE/MLE	KH-59M/ME
	Kh-25ML/MT	
	Kh-59ME/MK/MK2	
	Kh-58	
<i>Rocket Weapon System</i>	S-8KOM/BM/OM	S-8KOM/BM/OM
	S-13T/OF	S-13T/OF
	S-250FM-PU	S-250FM-PU
	S-80FP	
<i>Bomb Weapon Systems</i>	KAB-500-S-E	KAB-500KR
	KAB-500L	KAB-500OD
	KAB-500KR	KAB-1500KR
	KAB-500OD	KAB-1500L
	KAB-1500KR	FAB-500T
	KAB-1500L	FAB-500 M62
	FAB-500T	BETAB-500SHP
	FAB-500 M62	ODAB-500PM
	BETAB-500SHP	OFAB-250-270
	ODAB-500PM	OFAB-100-120
	OFAB-250-270	P-50T
	OFAB-100-120	RBK-500
	P-50T	SPBE-D
	RBK-500	
	SPBE-D	

6.2 Ammunition Comparison

The analysis of the destruction concluded the likely ordnance was an airburst munition; this discounts any Fuel-Air based systems such as the ODAB-500PM as well as incendiary weapon systems. The use of rocket and missile weapon systems have also been discounted as this contradicts evident Russian air doctrine at the time of the attack which restricts their deployment exclusively for strategic military targets [30]. Disregarded bomb-based munitions are provided in in Table 6-2, while Table 6-3 provides technical detail on the remaining potential systems which have been evaluated as part of this assessment. The technical detail has been provided by an open-source literature review, exact military specifications may vary.

Table 6-2 - Su-30 and Su-34 Discounted Aircraft Bomb Weapon Systems for Mariupol Drama Theatre Attack

Weapon System	Family	Weapon System Type	Reason for Exclusion
KAB-500OD	KAB	TV-Guided Fuel Air Bomb (500kg) [34]	Evidence does not indicate excessive fire that would be present after a fuel air explosion
KAB-1500KR	KAB	TV-Guided Bomb (1500kg) [34]	Payload excessive (440-650kg) for the calculated NEQ and level of damage observed
KAB-1500L	KAB	Laser Guided Bomb (1500kg) [34]	Payload excessive (440-650kg) for the calculated NEQ and level of damage observed
FAB-500T	FAB	High Explosive Blast Low Drag General Purpose Bomb [35]	First reported use in Ukraine is 2024 [36]
ODAB-500PM	ODAB	Parachute Guided Fuel Air Aerial Bomb [37]	Evidence does not indicate excessive fire that would be present after a fuel air explosion
OFAB-250-270	OFAB	High Explosive Fragmentation Bomb (250kg) [38]	While it would produce blast effects, since a portion of the energy is used to break the casing, it would not produce enough pressure to cause the level of destruction observed
OFAB-100-120	OFAB	High Explosive Fragmentation Bomb (100kg) [38]	While it would produce blast effects, since a portion of the energy is used to break the casing, it would not produce enough pressure to cause the level of destruction observed
P-50T	P	Practice Aircraft Bomb [39]	Practice Bomb would not provide the required blast effects to destroy a building
RBK-500	RBK	Aerial Bomb Carrier for Submunitions [40]	Evidence does not indicate the use of submunitions
SPBE-D	SPBE	Explosively Formed Projectile (EFP) Submunition [41]	Evidence does not indicate the use of an EFP
BETAB-500SHP	BETAB	Concrete Piercing Bomb [42]	This munition type is typically used for destroying concrete runways and would expect the presence of a crater. It can be used for reinforced concrete buildings, but the roof was not reinforced so it is unlikely it would have been used for a target like the theatre.

Table 6-3 - Technical Detail on Likely Ordnance Used During the Mariupol Drama Theatre Attack

Weapon System	Subcategory	Explosive Fill Composition	Explosive Fill Weight (kg)	TNT Equivalent (kg)	All Up Weight (kg)	Dimensions (m)	Guided or Unguided	Fuze Type
<i>KAB-500-S-E</i>	GPS Guided Bomb	TGAF-5M [43]	195 [44]	253.5	500 [44]	3x0.4 [44]	Guided [44]	Impact Fuze, with three delay types [44]
	Laser Guided Bomb	TGAF-5M [43]	100 [34]	130	500 [34]	3.05x0.4 [45]	Guided [34]	Impact Fuze, with three delay types [45]
	TV-Guided Bomb	TGAF-5M [46]	100 [34]]	130	520 [34]	3.1x0.35 [34]	Guided [34]	Impact Fuze, with three delay types [47]
<i>FAB-500 M62</i>	General Purpose Bomb with added Glide Modification Kit	TNT [40, 48] or TGAF-5M [49]	209 [40] or 207 [49]	209	497 [40]	2.47x0.4 [40]	Unguided but can be Guided if GPS navigation is included in the glide kit [50]	Electromagnetic Impact Fuze with delay [49, 51]
				269				

7 Assessment of Likely Candidate

7.1 Theoretical Pressure Assessment

An assessment has been conducted on the probable munitions in Table 6-3 to identify the theoretical incident and reflected pressure the weapon systems could produce. Table 7-1 summarises the calculations from 9Appendix B, highlighting that the systems could produce the threshold pressure of 10psi (68.95kPa) at a range of 18.39m.

Table 7-1 - Theoretical Peak Incident and Peak Reflected Pressure (kPa) at 18.39m From Likely Munitions Used in Mauripol Theatre Strike

<i>Weapon System</i>	<i>Explosive Fill Composition</i>	<i>Explosive Fill Weight (kg)</i>	<i>TNT Equivalent (kg)</i>	<i>Peak Incident Pressure (kPa)</i>	<i>Peak Reflected Pressure (kPa)</i>
<i>KAB-500-S-E</i>	TGAF-5M	195	253.5	87.06 - 95.89	233.42 - 260.29
<i>KAB-500L</i>	TGAF-5M	100	130	55.90 - 58.14	136.51 - 142.70
<i>KAB-500KR</i>	TGAF-5M	100	130	55.90 - 58.14	136.51 - 142.70
<i>FAB-500 M62</i>	TNT	209	209	76.39 - 82.53	198.80 - 216.65
<i>FAB-500 M62</i>	TGAF-5M	207	269	90.74 – 100.51	245.67 - 275.84

Although the KAB-500L and the KAB-500KR systems are incapable of producing sufficient incident overpressure for the level of structural damage, the confined nature of the detonation would have resulted in reflected pressures exceeding the 10psi (68.95kPa) threshold. Given the assessed intent to achieve significant structural damage, it is reasonable to conclude that the weapon system employed had sufficient NEQ to generate near-maximum pressure effects, consistent with the use of either the KAB-500-S-E or FAB-500 M62.

7.2 Guided vs Unguided Assessment

Given the centrally located internal detonation and the level of structural damage observed, the weapon system deployed had a degree of accuracy. Analysis was undertaken to evaluate whether an unguided system could account for the destruction observed or if the evidence directs to a guided system.

Guided weapon systems utilise on board guidance to direct them to an intended target with high accuracy [20, 23], with a typical Circular Error Probable (CEP) of less than 10m [20, 23, 52]. CEP is a standard measure of weapon system precision defined as the radius of a circle, centred around the intended target, within which 50% of munitions fired are expected to land [20, 23, 52]. The CEP of the likely munitions used on the Mariupol Theatre is provided in Table 7-2. Guided systems are typically deployed in precision strikes against high value assets to achieve strategic or tactical military objectives with fewer resources and reduced collateral damage [23, 52] or in urban environments to reduce civilian harm and infrastructure damage.

Table 7-2 - Circular Error Probable (CEP) of Likely Munitions

<i>Weapon System</i>	<i>CEP</i>
KAB-500-S-E	7-12m [44]
KAB-500L	7-10m [45]
KAB-500KR	4-7m [34]
FAB-500 M62	>30m [2]

Unguided systems follow a fixed ballistic trajectory and lack post-launch control, making them susceptible to environmental disturbances [53]. Their range and precision degrade significantly as the range to target increases [23]. These are often deployed en masse when widespread areas effects are required and are standard tactic for suppressing enemy formations or destroying large complexes over a significant area [52].

The precise nature of the strike on the theatre and the lack of nearby significant buildings indicates that a guided munition was used. While it is technically feasible for an unguided bomb to have struck the theatre under favourable environmental conditions, such as clear visibility and low wind, the probability of it impacting near the centre of the performance area is low, even with the Russian Airforce's established use of unguided munitions like the FAB-500 M62 [30, 54, 55].

Incorporating the required pressures to cause the level of structural damage observed, it is most likely that the KAB-500-S-E was used. The guidance system would have enabled an accurate strike and the NEQ would have ensured significant damage was caused.

8 Conclusion

This report aimed to identify the most probable ordnance used in the attack on the Mariupol Drama Theatre on 16th March 2022 through evaluation of blast effects, structural damage and weapon systems from specific delivery platforms. Despite the absence of direct site access, a robust methodical approach was applied.

Analysis of satellite imagery, debris distribution and structural failure patterns indicate that the munition penetrated through the roof of the performance space and detonated internally. The observed outward displacement of debris, catastrophic roof collapse and limited damage from the front of the building are consistent with an internal detonation within a confined or semi-confined environment. The lack of significant fire damage and a crater, suggest the use of an air burst air-to-surface munition with a delay fuze.

Blast calculations using the Kingery-Bulmash framework and supplementary methods provided a conservative free-field baseline to indicate an incident overpressure threshold of 10psi (68.95kPa) at 18.39m would require a minimum NEQ of 173-179kg of TNT. Consideration of reflected pressure effects would reduce the minimum NEQ to 48-50kg.

Comparative ordnance analysis evaluated probable weapon systems based on their explosive yield, delivery mechanism and the consistency with the damage observed. Missile, rocket, Fuel-Air and fragmentation systems were discounted. The level of accuracy required to achieve the centrally located internal detonation, alongside limited collateral damage strongly favoured a guided system. On this basis, the KAB-500-S-E was assessed to be the most likely weapon system used in the attack.

While uncertainties remain due to the incomplete data, the findings support the conclusion that the Mariupol Drama Theatre was destroyed by a precisely delivered air-to-surface munition designed to produce severe internal blast effects, consistent with deliberate targeting rather than incidental damage.

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Appendix A Technical Calculations for NEQ Determination

Determining the theoretical NEQ of a munition based on its blast pressure can be calculated using different methods, including:

- Kingery-Bulmash Blast Curves
- Mills Equation
- Established Blast Calculators

Each work on the Hopkinson-Cranz scaling law to correlate the distance from a detonation and the size of the explosive charge.

A.1 Determining Probable NEQ Using Kingery-Bulmash Curves

For an incident pressure of 10psi (68.95kPa), Figure A-1, shows the scaled distance, Z , is $3.3mkg^{-\frac{1}{3}}$.

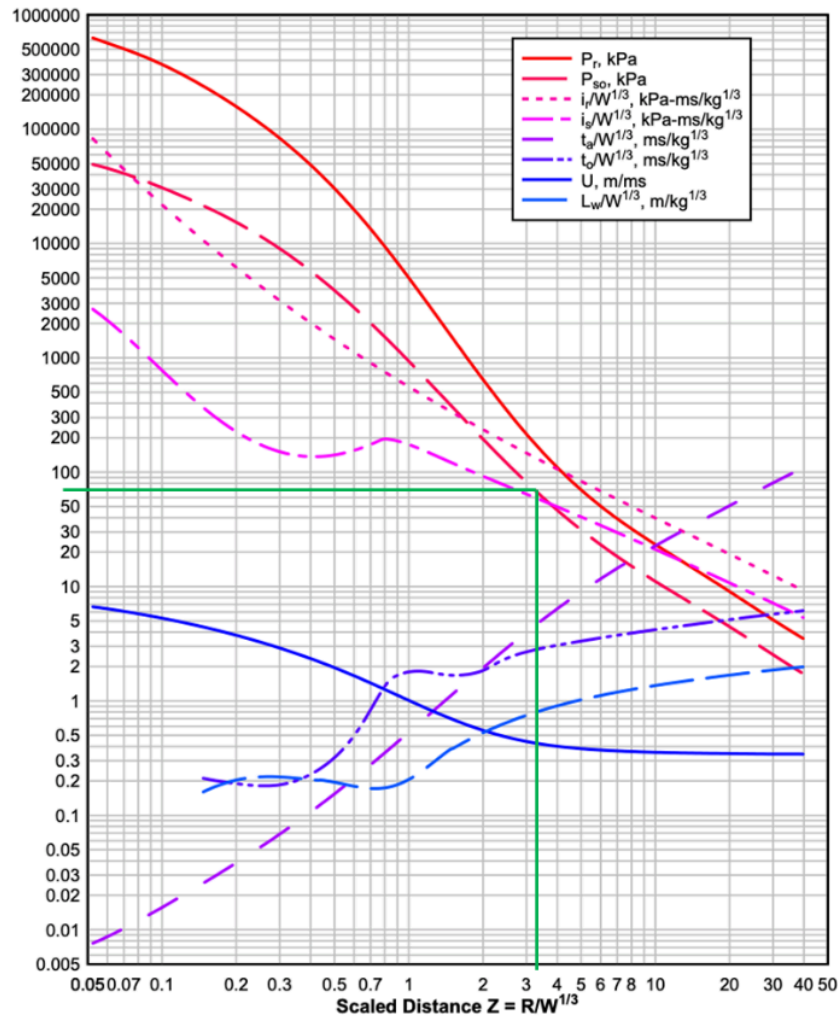


Figure A-1 - Kingery-Bulmash Curve Highlighting the Scaled Distance at an Incident Pressure of 10psi (68.95kPa)

Using the Hopkinson-Cranz Scaled Distance Formula (5-1), the NEQ can be determined at $Z = 3.3 \text{ m kg}^{-\frac{1}{3}}$ and $R = 18.39 \text{ m}$ with **A-1**.

$$W = \left(\frac{R}{Z} \right)^3$$

A-1

$$W = \left(\frac{18.39}{3.3} \right)^3$$

$W = 173.06 \text{ kg of TNT}$

A- 2

Based on this method, minimum NEQ required to cause the destruction of the Mariupol Theatre is 173.06kg of TNT equivalent.

A.2 Determining Probable NEQ Using Blast Calculator

Using a Blast Calculator provided by Brimstone Consultancy [56] (Figure A-2) to produce a blast Incident pressure of 10psi (68.95kPa) at 18.39m (scaled distance of $3.26 \text{ m kg}^{-\frac{1}{3}}$), it would require 179.34kg of TNT.

AIRBLAST PARAMETERS BY DISTANCE, BY NEQ & BY TNT EQUIVALENCE

Reference Documentation is:

"Airblast Parameters from TNT Spherical Air Burst & Hemispherical Surface Burst" by Charles N Kingery & Gerald Bulmash, Tech Report ARBRL-TR-02555 dated April 1984.

Gilbert F.Kinney, Kenneth J. Graham - Explosive Shocks in Air (2nd Edition)

INPUTS

Actual Stand-off Distance (D) [m]	18.39
Nett Explosive Quantity (Q) [kg]	179.34
TNT Equivalence Figure	1

OUTPUTS

	Air	Surface
Peak Incident Pressure (Ps) [kPa]	68.9543266	97.2464298
Incident Impulse (Is) [kPa.msec]	337.0156401	486.0745041
Peak Reflected Pressure (Pr) [kPa]	175.5462953	265.9893546
Reflected Impulse (Ir) [kPa.msec]	754.5787186	1148.1543243
Shock Front Velocity (U) [m/msec]	0.4279949	0.4600691
Arrival Time (Ta) [msec]	25.8808863	23.1159851
Positive Phase Duration (T+) [msec]	15.8179382	17.0392331

Figure A-2 - NEQ Determination Results from Brimstone Consultancy Blast Calculator

A.3 Determining Probable NEQ Using Mills Equation

The Mills equation (A- 3) [15], is typically used to calculate the incident pressure (P_{so}), in kPa, based on the scaled distance. If the pressure is known, it can also be used to calculate the scaled distance using A- 4.

$$P_{so} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \quad \text{A- 3}$$

Where,

$$Z = \frac{36}{P_{so}} + \sqrt[3]{-\frac{q}{2} + \sqrt{\Delta}} + \sqrt[3]{-\frac{q}{2} - \sqrt{\Delta}} \quad \text{A- 4}$$

Where,

$$q = -\frac{93312}{P_{so}^3} + \frac{4104}{P_{so}^2} - \frac{1172}{P_{so}} \quad \text{A- 5}$$

$$p = \frac{114}{P_{so}} - \frac{3888}{P_{so}^2} \quad \text{A- 6}$$

$$\Delta = \left(\frac{q}{2}\right)^2 + \left(\frac{p}{2}\right)^2 \quad \text{A- 7}$$

Therefore, for an incident pressure of 10psi (68.95kPa):

$$q = -\frac{93312}{P_{so}^3} + \frac{4104}{P_{so}^2} - \frac{1172}{P_{so}}$$

$$q = -\frac{93312}{68.95^3} + \frac{4104}{68.95^2} - \frac{1172}{68.95}$$

$$q = -16.42 \quad \text{A- 8}$$

$$p = \frac{114}{P_{so}} - \frac{3888}{P_{so}^2}$$

$$p = \frac{114}{68.95} - \frac{3888}{68.95^2}$$

$$p = 0.84 \quad \text{A- 9}$$

$$\Delta = \left(\frac{q}{2}\right)^2 + \left(\frac{p}{2}\right)^2$$

$$\Delta = \left(\frac{-16.42}{2}\right)^2 + \left(\frac{0.84}{2}\right)^2$$

$$\Delta = 67.58$$

A- 10

$$Z = \frac{36}{P_{so}} + \sqrt[3]{-\frac{q}{2} + \sqrt{\Delta}} + \sqrt[3]{-\frac{q}{2} - \sqrt{\Delta}}$$

$$Z = \frac{36}{68.95} + \sqrt[3]{-\frac{-16.42}{2} + \sqrt{67.58}} + \sqrt[3]{-\frac{-16.42}{2} - \sqrt{67.58}}$$

$$Z = 3.28 \text{ m kg}^{-\frac{1}{3}}$$

A- 11

Using the rearranged Hopkinson-Cranz Scaled Distance Formula (A- 1), the NEQ can be determined at $Z = 3.28 \text{ m kg}^{-\frac{1}{3}}$. And $R = 18.39 \text{ m}$.

$$W = \left(\frac{R}{Z}\right)^3$$

$$W = \left(\frac{18.39}{3.28}\right)^3$$

$$W = 175.6 \text{ kg of TNT}$$

A- 12

Based on this method, minimum NEQ required to cause the destruction of the Mariupol Theatre is 175.6kg of TNT equivalent.

A.4 Determining Probable NEQ Based on Reflected Pressure

Calculating the NEQ based on the reflected pressure is more complex than the incident pressure as it requires knowing the scaled distance, the incident pressure and the angle of incidence [14, 15]. Kingery-Bulmash provides a curve

for reflected pressure and as shown in Figure A-3 at a reflected pressure of 10psi (68.95kPa) the scaled distance is $5.0mkg^{-\frac{1}{3}}$.

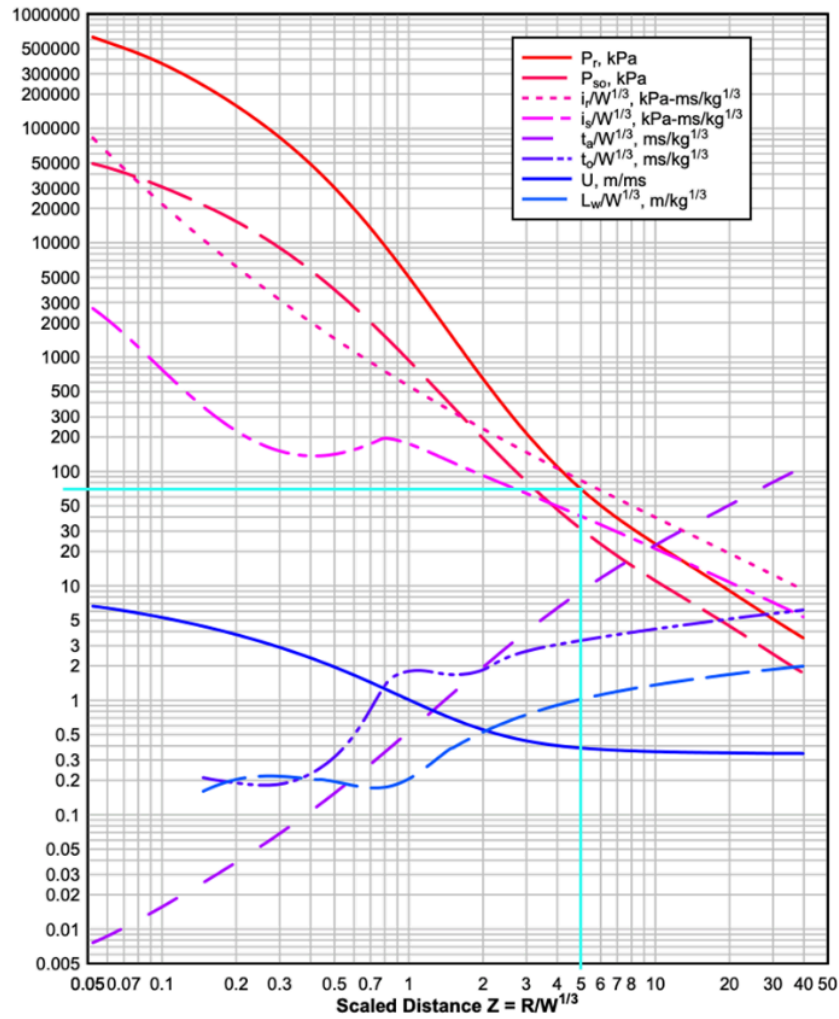


Figure A-3 - Kingery-Bulmash Curve Highlighting the Scaled Distance at a Reflected Pressure of 10psi (68.95kPa)

Using the rearranged Hopkinson-Cranz Scaled Distance Formula (A- 1), the NEQ can be determined at $Z = 5.0mkg^{-\frac{1}{3}}$ and $R = 18.39m$.

$$W = \left(\frac{R}{Z}\right)^3$$

$$W = \left(\frac{18.39}{5.0}\right)^3$$

$$W = 49.75kg \text{ of TNT}$$

A- 13

Based on this method, minimum NEQ required to cause the destruction of the Mariupol Theatre is 49.75kg of TNT equivalent.

Using the Blast Calculator [56] to produce a blast reflected pressure of 10psi (68.95kPa) at 18.39m (scaled distance of $5.04mkg^{-\frac{1}{3}}$), it would require 48.55kg of TNT.

Appendix B Theoretical Pressure Calculations for Probable Munitions

The theoretical pressure calculations for the probable munitions have been conducted using different methods to illustrate the variance and uncertainty in theoretical calculations.

B.1 Determining Theoretical Pressure Calculations using Blast Calculator

The Brimstone Consultancy blast calculator [56] allows for the determination of incident and reflected pressure at a range of 18.39m. The results are shown in Table B-1.

Table B-1 - Theoretical Incident and Reflected Pressure for Probable Munitions Calculated Using Brimstone Consultancy Blast Calculator

Weapon System	TNT Equivalent (kg)	Scaled Distance (mkg^{-1/3})	P_{so} (kPa)	P_r (kPa)
KAB-500-S-E	253.5	2.91	87.06	233.42
KAB-500L	130	3.63	55.9	136.51
KAB-500KR	130	3.63	55.9	136.51
FAB-500 M62	209	3.10	76.39	198.80
FAB-500 M62	269	2.85	90.74	245.67

B.2 Determining Theoretical Pressure Calculations using Kinney-Graham Equation

As discussed in Section 5 - Technical Calculations, the Kingery-Bulmash framework provides semi-empirical formulas to determine incident pressure. These formulations are complex and require advance computer modelling. Kinney and Graham developed supplementary formulas [15] (A- 14) which also uses scaled distance from Hopkinson-Cranz (5-1) to determine the peak overpressure.

$$\frac{P_{so}}{P_a} = \frac{808[1 + (\frac{Z}{4.5})^2]}{\sqrt{1 + (\frac{Z}{0.048})^2} \times \sqrt{1 + (\frac{Z}{0.32})^2} \times \sqrt{1 + (\frac{Z}{1.35})^2}} \quad \text{A- 14}$$

Where P_{so} is peak incident pressure in bar and P_a is atmospheric pressure in bar.

For each of the probable munitions, the scaled distance was calculated using equation 5-1 at a range of 18.39m and the peak incident pressure was calculated using A- 14 at an atmospheric pressure of 1.014 bar. The results are presented in Table B-2.

Table B-2 - Theoretical Incident Pressure for Probable Munitions Calculated Using Kinney-Grahams Equation

Weapon System	TNT Equivalent (kg)	Scaled Distance (mkg^{-1/3})	$\frac{P_{so}}{P_a}$ (Bar)	P_{so} (Bar)	P_{so} (kPa)
KAB-500-S-E	253.5	2.91	0.87	0.88	88.40
KAB-500L	130	3.63	0.54	0.55	54.70
KAB-500KR	130	3.63	0.54	0.55	54.70
FAB-500 M62	209	3.10	0.76	0.77	76.71
FAB-500 M62	269	2.85	0.91	0.92	92.38

B.3 Determining Theoretical Peak Incident Pressure Using Mills Equation

Table B-3 provides the theoretical incident pressure calculated using Mills equation (A- 3).

**Table B-3 - Theoretical incident pressure for Probable Munitions Calculated
Using Mills Equation**

<i>Weapon System</i>	<i>TNT Equivalent (kg)</i>	<i>Scaled Distance (mkg^{-1/3})</i>	<i>P_{so} (kPa)</i>
<i>KAB-500-S-E</i>	253.5	2.91	95.89
<i>KAB-500L</i>	130	3.63	58.14
<i>KAB-500KR</i>	130	3.63	58.14
<i>FAB-500 M62</i>	209	3.10	82.53
<i>FAB-500 M62</i>	269	2.85	100.51

B.4 Determining Theoretical Peak Reflected Pressure

Reflected pressure is typically calculated based on the angle the pressure wave hits a surface (angle of incidence) and the peak incident pressure. For peak reflected pressure the angle of incidence is zero [15] and can be calculated using equation A- 15.

$$P_r = 2P_{so} \frac{4P_{so} + 7P_o}{P_{so} + 7P_o} \quad \text{A- 15}$$

Where P_r is peak reflected pressure and P_o is ambient or atmospheric pressure.

The theoretical peak reflected pressure of the probable munitions in Table B-4 was calculated using the theoretical incident pressures from Table B-2 and Table B-3 and Equation A- 15.

Table B-4 - Theoretical Calculated Reflected Pressure for Probable Munitions

<i>Weapon System</i>	<i>Kinney Graham Method</i>		<i>Mills Method</i>	
	<i>P_{so} (kPa)</i>	<i>P_r (kPa)</i>	<i>P_{so} (kPa)</i>	<i>P_r (kPa)</i>
<i>KAB-500-S-E</i>	88.40	235.56	95.89	260.29
<i>KAB-500L</i>	54.70	132.90	58.14	142.70
<i>KAB-500KR</i>	54.70	132.90	58.14	142.70
<i>FAB-500 M62</i>	76.71	198.32	82.53	216.65
<i>FAB-500 M62</i>	92.38	248.61	100.51	275.84

FINAL GRADE

90/100

GENERAL COMMENTS

Hi Emalie,

As ever, this was an outstanding submission, which clearly demonstrated to me the depth and rigour you apply to each assignment. You clearly understand the subject matter and can systematically drive argument to sound conclusions. You leave me in no doubt that the munition is most likely a KAB-500-SE.

The high grade awarded is entirely justifiable and your rubric scores are shown below:

Engagement with literature skills

13/15. Exceptional engagement with an extensive range of relevant and credible literature, informed by the latest research. High-level referencing skills consistently and professionally applied.

Knowledge and Understanding

23/25. Exceptionally coherent and detailed knowledge and systematic understanding of the principles and theories of the subject, well-informed by current research and scholarship. A critical, sophisticated and nuanced awareness of the ambiguities and limitations of knowledge .

Cognitive and Intellectual Skills 18/20. Exceptional critical thinking, analysis, synthesis and evaluation based on judiciously selected evidence. Ability to investigate contradictory or incomplete information and make strong, persuasive, arguments and sophisticated, nuanced, judgements. Evidence of independent thought and ability to 'see beyond the

question', suggesting an outstanding grasp of the broader field and wider concepts.

Practical Application 18/20. Exceptional levels of application and deployment skills in unpredictable, practical contexts, drawing skilfully on the latest research within the discipline. Can identify complex problems and propose sophisticated solutions. Assimilation and development of cutting edge processes and techniques.

Transferrable Skills 18/20. Can communicate with an exceptionally high level of professionalism. Work is exceptionally coherent, very fluent and is presented professionally. Demonstrates exceptional graduate employment skills and an appetite for further development.

In detail:

1. Excellent executive summary, which outlined the key aspects of the submission. You credibly identify a KAB series warhead as the likely candidate.

2. Great structure applied to the problem, which was clearly presented and easy to follow. You used appropriate figures, tables and equations, cross referencing each accurately.

3. In the introduction, you could have used 'incident' before overpressure in the second paragraph. This delineates more appropriately.

4. Figures 2-1, 2-2 and 3-1 demonstrate the isolated status of the theatre. Well done. I also liked the research you conducted into the structural aspects of the building. This allows us to consider, perhaps

10 - 14 PSI and the loading, with 14 PSI being the upper threshold for what you have described.

5. Very useful description of witness statements, with a credible reference which underpinned the disparity in what people actually experience.

6. From the open source literature, your analysis of the type of munition is sound. Not cruise missile, FAE, thermobaric etc.

7. I particularly liked the way you attempt to apply geometry to the blast damage. There is a definite curvature, which supports an air blast within the structure but not a surface burst. Indeed, the attitude of the damage dispersal demonstrates (potentially) the direction from which the 'cylinder' came, or its orientation at detonation.

8. Excellent description of internal blast. Your extra reading is most eloquently displayed in scaled venting ratios. Definitely a confined blast in relation to the volume of space.

9. Pedantic comment. Y-axis units on Figure 5-1. Also, think about annotating the Z value on the graph to bring the sweet spot you discuss to life in the main text, not the Appendix.

10. Watch for type-o such as 9 Appendix A.

11. Useful relegation of superfluous data to Appendices. On checking the data provided is accurate.

12. Table 6-1 is very powerful and clearly depicts what the Su-30/34 series are able to carry.

13. Table 6-2 is well thought out, particularly the exclusion criteria. Good analysis on the first reported use of the FAB, so we are looking at the KAB potentially. Can't discount the FAB, but reporting and open source intelligence strongly suggests it may not be.

14. Same deduction following from table 6-3 I presume.

15. CEP suggests guided given the scenarios.

16. Very strong conclusion.

17. Exceptionally well referenced, with good mix of credible vs open source.

18. Appendices well put together. All content checked and accurate.

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