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The Center for Spatial Technologies

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EXPLOSIVE ENGINEERING ASSESSMENT -
DONETSK REGIONAL ACADEMIC DRAMA THEATRE IN MARIUPOL, UKRAINE

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Explosion Summary

The alleged attack against Mariupol Drama Theatre was an air strike, most likely carried out by an SU-series Russian Federation fighter aircraft. The aircraft approached from a Westerly direction and dropped one, or possibly two, 500kg bombs fitted with delay fuzes from mid-altitude. The bombs were likely guided, with the KAB-500S-E fitting the engagement scenario within Russian Federation air warfare doctrine. However, unguided bombs such as the FAB-500 M62 cannot be excluded, given their CEP and the theatre's footprint.

The bare explosive charge mass required of the ordnance was at least 114kg TNT. Based on blast warhead case thickness, this extrapolates to a warhead net-explosive quantity (NEQ) above 156kg TNT.

The bombs penetrated the roof of the performing area to the east of the building and detonated within milliseconds. Given ordnance speed of descent, the type of delay fuze incorporated, and the damage inflicted by the blast, the bombs detonated in flight, not on contact with the ground, thereby generating a spherical air burst commensurate with the geometry of the warhead.

Blast damage is consistent with up to two bombs detonating in proximity, with incident peak overpressures well above the failure threshold of the building's structure. Reflected blast overpressures and their associated impulse would have been devastating. The attack was not perpetrated within the theatre, nor was a thermobaric warhead used. The theatre's isolated location compared to other buildings, suggests it was the chosen target for the air strike.

Background

1. In accordance with our agreement dated 9th November 2022, this paper details the explosive engineering findings based on evidence from The Center for Spatial Technologies (CST).

Evidential Review

Mariupol Theatre

2. **Location**. Mariupol Theatre is a typical reinforced masonry structure, which is situated geographically in an east-west direction. It is built in an open area, with no other obvious structure within 100m. As such, it is considered an isolated target for both unguided and precision bombing.

3. **Dimensions**. The dimensions of the theatre provided in the evidence are as follows:

   a. Width (performing area) (N-S) – 36.78m
   b. Width (entrance) (N-S) – 28.78m
   c. Length (E-W) – 68.17m
   d. Height (at theatre end) – 21.96m

The theatre can be considered as two discrete sections, comprising 1) a performing area, and 2) an entrance. The performing area occupies a volume of approximately 15,000 m^3 (35.4m x 22.355m x 18.978m) – Figure 1 – whilst the entrance comprises several layers of internally supported structures. The performing area sits to the eastern end of the structure and occupies approximately one-half of the ground space. Since it is a performing area, its engineering design is to facilitate the transmission of sound, and to amplify that sound to a listening audience sitting/standing forwards from the entrance. As such, it is a large open structure with a girder roof support (see Figure 2). In terms of explosion energy, the roof decking material above the performing area (less the steel girders) can be considered frangible. Frangible within this context means that the decking would provide little resistance to blast, being forced upwards in small pieces, with the steel girders falling inwards due to their small cross-sectional area and high density.

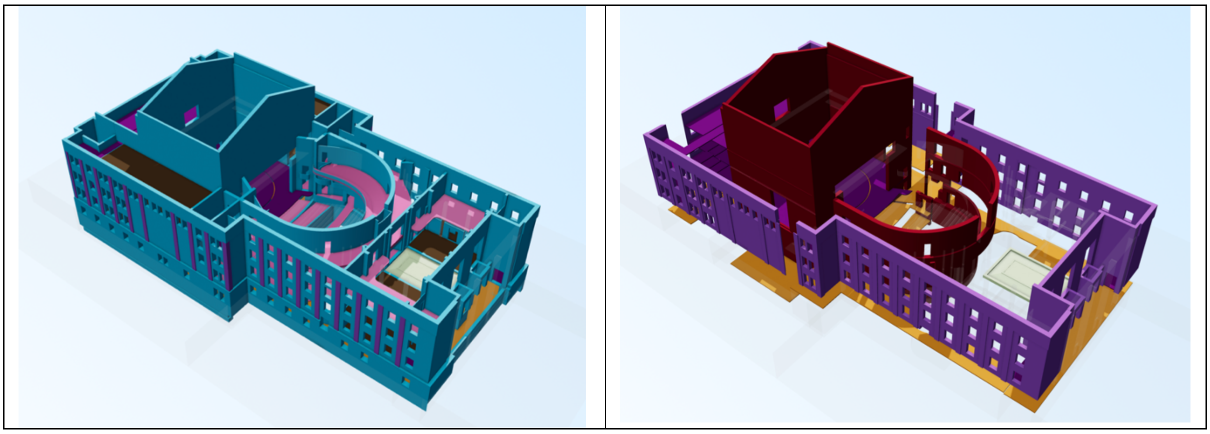

Figure 1: Structural view of Mariupol Theatre (performing area and entrance)

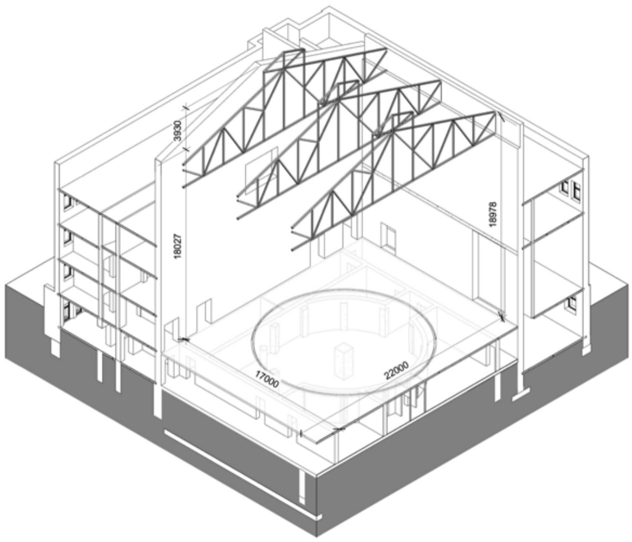

Figure 2: Schematic of performing area and roof supports

4. **Damage Area**. The evidence clearly shows an explosion having occurred in the region of the performing area (see Figure 3). The explosion occurred within the structure, between the roof space and the performing stage. This is borne out by the way in which there is no obvious crater, and how debris has been thrown outwards to the north, south and west. Specific damage can be seen in Figure 4, which points out girders fallen inwards, roof decking strewn around, and the thin metal roof covering perforated with fragmentation from a thin-cased munition detonating within the structure, <u>**not**</u> outside. It is important to note that the performing area facilitates the propagation of the incident blast overpressure and associated blast wave, closely followed by reflected overpressures. The performing area provides the ideal location to exploit the incident and reflected blast overpressures. It is therefore possible to state, with a high degree of confidence, that the explosion occurred above

the performing stage, and that at least one large item of ordnance entered through the frangible roof, detonating shortly thereafter.

Figure 3: Mariupol theatre viewed East to West, with explosion epicentre in region of performing area

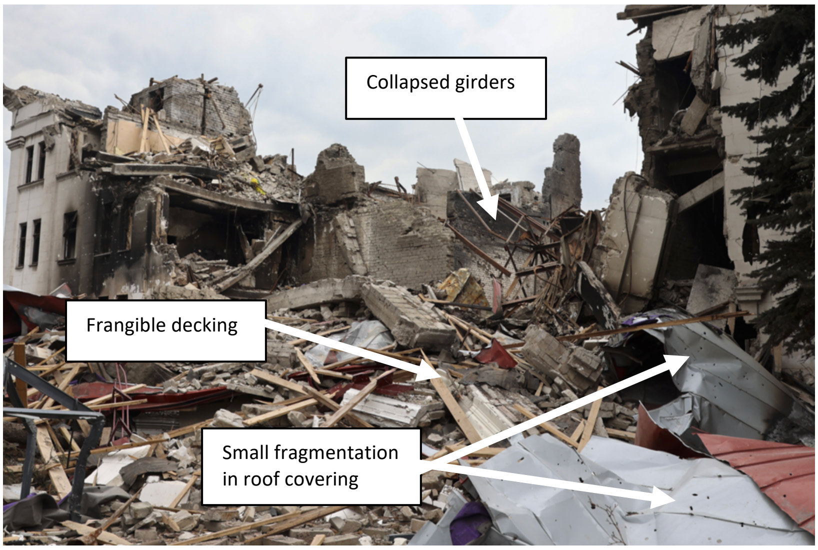

Figure 4: Collapsed roof structure and debris demonstrating evidence of internal explosion

5. **Witness Testimony**. 87% of witness statements corroborate one audible explosion, with the remainder stating that they heard two explosions in rapid succession. This is not unusual for a traumatic event (Marr, Otgarr, Sauerland, & Hope, 2021). However, any disparity should not detract from logical argument since the explosion is a single footprint of devastation, whether from one or two items of ordnance. This will be explained further in the section discussing air dropped munitions and their precision/accuracy.

6. **Damage Parameters**. This is clearly an explosion involving a large warhead. But how large? To cause the almost complete destruction of a structure such as Mariupol Drama Theatre, which Figure 3 demonstrates, an incident blast overpressure between **7 and 10 PSI** would be required at a radius approaching one-half the building diameter[1]. In other words, at least 18.4m (0.5 the distance of paragraph 3a) if one takes the centre of the performing stage as the reference point. It is also important to note that reflected blast overpressures exceed incident overpressures, leading to even greater

[1] A blast overpressure between 7 and 10PSI is equivalent to between 48.26 and 69.8KPa respectively

damage (see the summary of blast theory at Annex A). Further information on damage criteria applicable to the theatre can be found at open source (GICHD, Explosive Weapon Effects, 2017).

7. **Blast wave geometry**. The damage (Figure 3 and Figure 5) is typical of that caused by a cylindrical warhead detonated at its forward end (Carlucci & Jacobson, 2008) (Knock & Davies, 2013). The precise point of detonation lies somewhere between the ceiling and floor of the theatre and within the ***RED*** shaded area in Figure 5. This would be typical of a blast warhead of military design, comprising a delay fuze, which would function a few milliseconds after impact with the first obstruction (in this instance the theatre roof). The fuze would aim to allow the ordnance to penetrate the structure, thereby delivering the explosive power internally and maximising blast wave formation and reflected overpressures. The precise location of the detonation is difficult to determine, although it cannot be a surface burst since there is no visible crater within the evidence. Therefore, the event occurred within the acoustic space described in paragraph 4. The warhead's trajectory is likely 15-30^{o} to the vertical, judging by the debris scattered externally to the building, and how the roof structure over the entrance area has deformed (Figure 5). Had the point of detonation been in the entrance area then the roof over that structure would have suffered the same fate as the performing area. To achieve such damage, it is likely that the ordnance was discharged from a delivery system external to the theatre, and from a westerly direction. As such, it is extremely unlikely that an act of terrorism occurred within the building, unless the occupants were able to suspend a large mass of explosives above the performing stage.

Figure 5: Schematic view west-east and likely position of warhead detonation

The diagram below (Figure 6) indicates how a cylindrical blast warhead would begin to break apart over a period of micro-seconds following initiation at the forward end. Fragmentation of the case would be determined by its thickness and the detonation velocity of the explosive filling. The direction of fragmentation would depend upon Gurney and Taylor equations – not for this report. As stated in paragraph 4, a blast warhead's case is thin to minimise explosion energy losses, and fragmentation is therefore generally small (Mott, 1947).

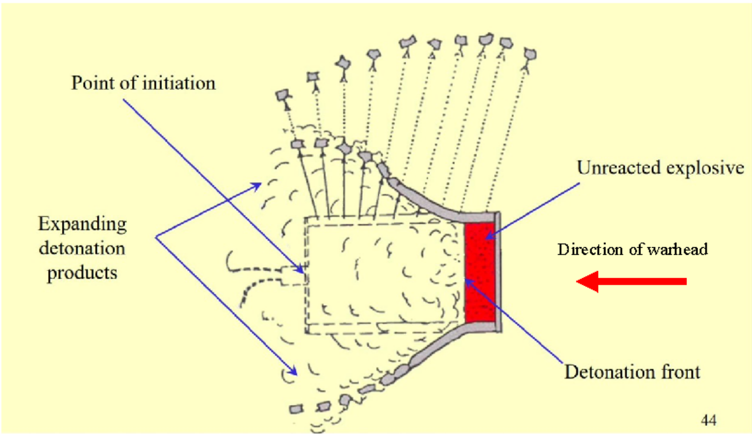

Figure 6: Diagram demonstrating the detonation of a cylindrical warhead from an end point initiation

Initial Blast Overpressure Calculations

8. **Kingery-Bulmash**. Equations to estimate blast over-pressure for engineering applications have been developed by Charles Kingery and Gerald Bulmash (Kingery & Bulmash, 1984). These equations are widely accepted as authoritative engineering predictions for determining free-field pressures and loads on structures. The Kingery-Bulmash (K-B) equations have been developed for TNT-equivalency (TNTe), to reflect the differences in explosive strength of different explosive formulations (such as TNT, TORPEX, HMX, TGAF-5 and ammonium nitrate). The amount of an explosive is transferred to the equivalent amount of TNT by multiplication with a certain factor, derived theoretically or from experimental values.

9. **Bare Charge Mass**. Several terms such as Net Explosive Quantity (NEQ) and Net Explosive Weight (NEW) have been used by authors to describe events. However, they can be misleading since it is necessary to understand the effect of a munition's case on blast. The thicker the case, the greater the mass of explosive necessary to deliver the overpressure required at the target (Mott, 1947). As such, it is the bare explosive charge mass that shall determine the overpressure required at a certain distance. By calculating the bare charge mass required for a given overpressure (W_b), it is then possible to accurately identify the warhead (Equation 1). This can be calculated using the following equation and is dependent upon the charge mass (*c*) and the mass of the case (*m*) using TNT as the standard:

$$W_b = 1.19 \left(\frac{1 + M_r(1 - M_c)}{1 + M_r} \right) c$$

Equation 1: Calculation for determine the bare explosive charge mass for a given warhead

Where M_r= the ratio of mass of charge to mass of case (*m/c*),
c = the actual mass of the charge,
m = actual mass of warhead case, and
M_c= 1 when M_r>1 and *m/c* when M_r<1

This equation is used within the detailed calculations underpinning this paper.

10. **Hopkinson-Cranz Scaled Distance**. Paragraph 6 states that structural damage of this significance must be delivered by a warhead capable of inflicting an incident overpressure between 7

and 10 PSI at 18m from the point of detonation. Using K-B scaled distance and graphs (Annex B) a minimum bare charge mass W_b of 114 kg TNT would be required to produce an overpressure of such magnitude at that distance. This has been derived from the Hopkinson-Cranz equation:

$$Z = \frac{R}{\sqrt[3]{W_b}}$$

Equation 2: Scaled Distance

Where Z = the scaled distance, R = the distance in metres at which the incident overpressure is required, and W_b is the bare charge mass (TNT in kg).

11. Based on Mariupol Drama Theatre, a scaled distance of approximately 3.83 m $kg^{-1/3}$ is required at 18m to deliver an incident overpressure of 68.9KPa (10 PSI). As can be observed from Table 1, the reflected overpressure for such a bare charge is twice that required to severely damage and demolish a reinforced structure. It is also important to note that at a scaled distance of > 3.5 $mkg^{-1/3}$ for a cylindrical charge, the geometry of the blast wave is 'healing' to that of a spherical air burst (Knock & Davies, 2013), making mathematical calculations much simpler.

TNT weight for pressure (kg)	114
Incident Pressure (KPa)	53.56 (10 PSI)
Reflected Pressure (KPa)	129.77 (19 PSI)
Shock wave velocity (ms^{-1})	410
Incident impulse (KPa-ms)	258.2
Reflected impulse (KPa-ms)	560.96
Arrival time at 18.4m (ms)	27.52
Positive Duration (T+) ms	14.42

Table 1: Blast parameters for scaled distance of Z=3.83 (spherical blast waves)

12. **Net Explosive Quantity (NEQ)**. NEQ is the total mass of explosive components within a munition. This includes the main charge, booster, and associated initiation mechanisms. Now that the basic parameters for overpressure, scaled distance and bare charge mass have been identified, the likely NEQ of the ordnance and the type of delivery system can be established. Whilst it is possible that there could have been more than one explosion (see paragraph 5), this can be determined more accurately by looking at the delivery system and understanding how one item of ordnance may interact with the other. Whatever the outcome, two warheads detonating within milliseconds (ms) of one another would not increase the incident overpressure significantly, but produce an impulse of much longer duration.

Types of Ordnance used in Ukraine by the Russian Federation

13. **Open-Source Review**. An open-source literature review on the types of Russian Federation air-dropped munitions currently used in Ukraine has been conducted (GICHD, Explosive Ordnance Guide for Ukraine - 1st Edition, 2022) to determine those that have an NEQ commensurate with a bare charge mass of greater than 114 kg TNT. These are shown in Table 2. The following systems can be discounted for the reasons stated, which somewhat narrows the field of contenders:

a. ***Artillery Rockets***. Not supported by witness testimony. Indirect fire, low precision, low accuracy.

b. ***Cruise Missile***. Russian Federation troops were operating in the vicinity. Armoured/ Mechanised infantry doctrine in Ukraine excludes using a cruise missile[2] under such circumstances.

c. ***Thermobaric/Incendiary/Fuel-Air***. Not supported by witness testimony or damage demonstrated by pictorial evidence. With a thermobaric, incendiary or FAE system, any fire would have been instantaneous. Witness testimony states that the fire commenced after 20 minutes.

d. ***Fragmenting Warheads***. Fragmenting warheads require explosive energy to break apart the case. In many instances, up to 50% of the explosive energy can be expended. As such, a fragmenting warhead would not be chosen doctrinally to defeat a building. A blast warhead would be used, and by design is a thin-walled cylinder (with warhead length to diameter ratio (L/D) > 2), allowing optimum energy transmission from the explosive to the surroundings.

e. ***OFAB-250 Air Dropped Bomb***. The NEQ is insufficient for the incident overpressures required, even with two bombs detonating in proximity.

Type of Ordnance	Delay Fuze	Guided or Unguided	Explosive Filling	NEQ (kg)	Dimensions (m)	Photograph
FAB-500 M62	Yes	Unguided	TNT TGAF-5 (207)	300 269	Diameter ø 0.4 Length 2.47 Warhead L/D > 2	
OFAB-500 M54	Yes	Unguided	TNT	250	ø 0.45 Length 2.385 Warhead L/D>2	
OFAB-500 M62	Yes	Unguided	TGAF-5 (120)	156	ø 0.4 Length 2.41 Warhead L/D>2	
OFAB-500U	N/K	Unguided	TNT	230	ø 0.4 Length 2.3 Warhead L/D>2	
KAB-500S-E	Yes	Guided CEP 7-12m	TGAF-5 (195)	253	ø 0.4 Length 3.0 Warhead L/D>2	

Table 2: Summary of likely types of Ordnance Used

The delay fuze for typical Russian Federation air dropped munitions (for example the AVU-ETM fuze) has 3 settings: 0s (impact or SQ); 0.01-0.04s (short delay); and 0.06-0.09s (middle delay – factory pre-set) dependent upon the structure to be defeated (Arcon Partners Ltd, 2022).

14. **Precision versus unguided bombs**. The terms 'accuracy' and 'precision' have two distinct meanings, often understood respectively as the ability to hit a desired target, and the ability to hit that target consistently. An unguided bomb can have high accuracy, but this is often accompanied by low precision. As such Russian Federation unguided bombs may have a Circular Error Probable (CEP) of

[2] 'Children' Amnesty International report EUR 50/5713/2022 dated 26th March 2022 provides excellent data on other implausible theories from pages 39 – 41.

>30m, although a trained pilot on a straight run[3] could strike a target the size of Mariupol Drama Theatre twice with a pair of unguided bombs. The impact damage does suggest a straight run. A guided bomb will have a much higher degree of accuracy and precision, with the KAB-500 series CEP between 7 and 12m. This means that a pair of KAB-500 would most certainly hit an alleged target the size of Mariupol Drama Theatre within that CEP. However, the engagement scenario supports the plausibility of precision or unguided bombs. Discussion should therefore focus more on why the theatre was selected as a target since other likely target buildings fall outside the CEP distance for unguided and guided bombs. As such, there is no mistake that the theatre **was** the intended target.

15. **Types of Delivery System**. Reporting suggests several delivery systems, such as the Su-24 Fencer, Su-34 Fullback, and the Su-35 Flanker, as well as upgraded Flankers and MiG-35s. Following a discussion with a subject matter expert in air-dropped weapon systems[4], the prime candidate aircraft would be the two-seat Su-34 given that Russian Federation state media has been keen to show videos of this aircraft carrying out bombing missions in Ukraine. The Su-34 would normally carry two bombs described in Table 2, releasing them singularly or in pairs. If the KAB-500 is considered, then the Su-34 can carry both the KAB-500L (laser designated/guided) and KAB-500S GLONASS (i.e., GPS) guided bombs, and these have been used frequently in Syria (see Figure 7). As such, pilots are experienced in their deployment and use. All FAB/KAB-500 bombs carry an impact fuze or a delay fuze (with three settings). If two bombs were to be dropped onto the same target, the release interval would have to be small as the explosion of the first bomb could risk triggering the fuze of the second bomb before it had adequately penetrated the desired target. If it is proven that there were two explosions very close together as stated by 13% of witnesses, then it is likely that it would have been a pair of KAB-500 guided bombs released simultaneously. Unguided bombs would not be expected to land so close together in these circumstances. Tactically, it is likely that it would be a medium altitude release at a range for the bombs (not an unguided version) of 7-9km from the target at an altitude of ~5000m. GPS guidance would not require the aircraft to stay in the vicinity of the target. The bomb flight time would be about 20-30 secs.

Figure 7: KAB-500S-E being fitted to Su-34 Flanker (2017)

16. **Types of Conventional Explosive Filling**. The FAB and KAB blast warheads contain TNT or TGAF-5. Whilst TNT is universally understood, TGAF-5 is a filling designed to enhance blast by adding

[3] from an easterly or westerly direction

[4] Targeting specialist – name withheld

aluminium powder to a mixture of TNT and RDX. Whilst the chemistry is not required here, TGAF-5 provides a more efficient blast warhead that TNT since it generates a much higher heat of explosion (approximately 1.3 TNTe).

Explosion Modelling

17. Based on open-source data within Table 2, the parameters for FAB-500 and KAB-500 were entered into the explosive modelling calculations (see Table 3). OFAB-500U was not progressed as its TNTe is not dissimilar to FAB-500M62-TGAF. For a 400mm ø cylindrical warhead, an overall case thickness for the bomb must be determined to allow calculations to progress. The case must be thick enough to support the bomb in service use, allow aerodynamic flight and penetration after launch, yet absorb minimum explosion energy. Research of available literature and the application of structural mechanics to low carbon steel munition casings suggests a case thickness of 10 – 15mm (CAT-UXO, 2022) (Arcon Ltd, 2022). The following results were obtained for 400mm ø warheads comprising TNT and TGAF-5, travelling with a forward dynamic velocity of approximately 250ms^{-1}.

Warhead	Explosive Filling	NEQ (*TNTe*) (kg)	Bare charge equivalence (*c*) (kg)	Peak Incident Overpressure at 18.4m (KPa (PSI))	Peak Reflected Overpressure at 18.4m (KPA(PSI))	Remarks
FAB-500 M62	TNT	300	261.36	88.86 (13)	239.37 (34)	One singular warhead exceeds the overpressure required
FAB-500 M62	TGAF-5	269	235.02	82.62 (12)	218.84 (32)	One singular warhead exceeds the overpressure required
OFAB-500 M62	TGAF-5	156	121.69	53.54 (8)	129.7 (18)	One singular warhead exceeds the overpressure required
KAB-500 S-E	TGAF-5	253	198.28	73.65 (11)	190.15 (28)	One singular warhead exceeds the overpressure required

Table 3: Comparison of air-dropped ordnance by incident overpressure

As can be seen, one KAB-500S-E warhead can deliver an overpressure more than that required to overmatch the theatre's structure (11 PSI). This, combined with a CEP < 12m, makes it the most plausible candidate for precision and accuracy. The OFAB-500 M62 sits on the limit of overpressure tolerance (8 PSI) and would unlikely be chosen as the candidate ordnance (20% target overmatch preferred).

Conclusions

18. From the evidence provided, one or a pair of cylindrical blast warheads were likely dropped from an aviation platform on Mariupol Drama Theatre. This statement is consistent with Russian Federation air warfare doctrine in Ukraine.

19. The warhead(s) detonated within the theatre as an airburst, not a ground burst.

20. The damage is consistent with a TNT bare charge mass > 114 kg, which can produce overpressures above 68.9KPa at 18m (the minimum radius for almost complete destruction).

21. Whilst it is difficult to discount unguided ordnance (such as the FAB-500) it is more plausible that one, or a pair, of KAB-500S-E guided bombs were dropped on Mariupol Drama Theatre given their CEP. These warheads have an NEQ of 253kg (198kg TNT bare charge mass) and produce more than 11 PSI incident overpressure at 18m.

22. Whichever item of ordnance was used, Mariupol Drama Theatre was an isolated structure, suggesting that an aircraft carrying guided or unguided bombs had designated the building as a target. The reason why remains unclear, and comes down to military necessity, proportionality, distinction, and humanity.

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Annex A- Blast Wave Theory

1. One of the most critical parameters for blast loading computations is the distance of the detonation point from the structure of interest. The peak pressure value and velocity of the blast wave decrease rapidly by increasing the distance between the blast source and the target surface (see Figure 8). Very roughly, the pressure diminishes with an inverse cube relationship at distance from the seat of explosion (double the distance from the seat of explosion and the observed blast effects reduce by a factor of 2^3 (8)). The effect of distance on blast characteristics can be considered by the introduction of scaling laws, which I have used in the calculations.

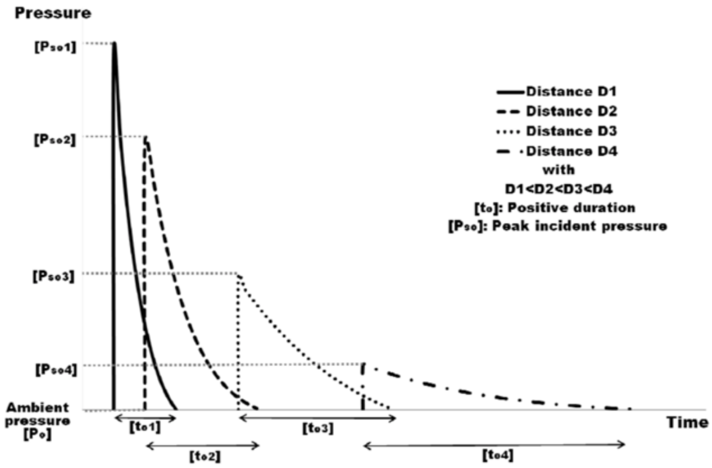

Figure 8: Pressure-Time curve of an ideal blast wave

2. As a blast wave travels through air, decreasing in speed and peak pressure value, it encircles every object/structure that lies within its range. The load that has to be withstood by a structure depends on various parameters, such as the type and weight of the explosive charge, the distance from the detonation point, the geometry of the blast wave pertinent to the structure, the type of structure, the interaction of the wave with the environment (a blast wave travelling through a tunnel, corridor, trench or street will decay much more slowly than in the open) and the ground. When the blast wave comes to contact with a rigid surface the pressure that is reflected is larger than the incident peak pressure (see Figure 9). Reflected pressure for explosive detonations can be almost 13 times greater than peak incident pressures and, for all explosions, the reflected pressure coefficients are significantly greater closer to the explosion – more damage close in, less further out. There are many reasons for this, and we need to understand that in a strong blast wave, such as Mariupol, the shock wave is a non-linear phenomenon, leading to constructive and destructive interference, particularly if there are two explosions in proximity. In other words, there would have been much higher reflected pressure values in some parts of the building and less in others as the blast wave propagated outwards.

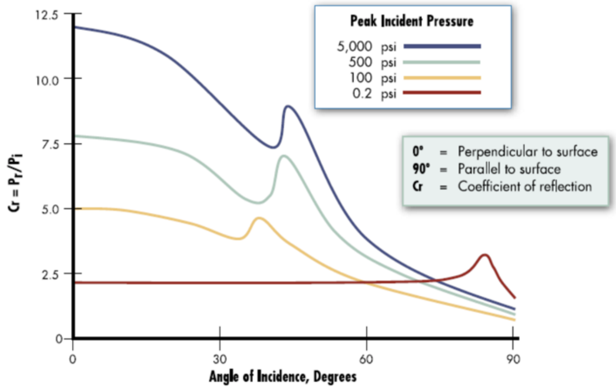

Figure 9: A representation of reflected pressures from structures

3. For calculation, I use the most widely accepted approach for the determination of blast parameters. That is the one proposed by Kingery-Bulmash[5]. Their paper includes formulations for both spherical (free air bursts) and hemispherical pressure waves (surface bursts) and provide the values of incident and reflected pressures as well as several other parameters. Kingery-Bulmash curves are accurate out to scaled distances Z = 40 $m/kg^{1/3}$

5 Kingery C. N., Bulmash G., (1984) "Technical report ARBRL-TR-02555: Air blast parameters from TNT spherical air burst and hemispherical burst", AD-B082 713, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

Annex B - K-B Calculations for Cylindrical Warhead – ø 40mm

Calculation of Warhead Parameters — Calculate and Print

Cylindrical Warhead

Geometrical and Physical Parameters

charge diameter	0.370	m	**Case material**	Mild Steel (low carbon)				
case thickness	0.015	m	**Case Density**	7860	kg/m^3			
warhead diameter	0.400	m	**Explosive**	TNT		**VoD**	7000	m/s
warhead length	0.800	m	**Explosive Density**	1700	kg/m^3	**Gurney constant**	2600	m/s
			mass of explosive	146.248	kg			
			mass of case	114.096	kg			
			mass HE/mass case	1.282		**total mass**	260.344	kg
point of initiation	centre face front							

Static Warhead			**Dynamic Warhead**					
fragment velocity	2298	m/s	**Warhead velocity**	250.0	m/s			
Taylor angle (front)	0.0	°	**Frag velocity (front)**	2311.6	m/s	**Ejection angle (front)**	6.2	°
Taylor angle (rear)	-9.2	°	**Frag velocity (rear)**	2271.2	m/s	**Ejection angle (rear)**	-3.0	°
Static beam angle	9.2	°				**Dynamic beam angle**	9.2	°

Fragment Effectiveness

Shape of fragment	cube edge on		**Drag coefficient**	1.1				
length of side =	1.50E-02	m	**Medium**	air - sea level				
Area of fragment	3.15E-04	m^2	**Medium Density**	1.206	kg m^-3			
Volume of fragment	3.38E-06	m^3						
Mass of fragment	2.65E-02	kg						
Critical energy density	3	J/mm^2	**Initial velocity**	2312.0	m/s	**Initial energy density**	225.1	J/mm^2
			Final velocity	267.0	m/s	**Final energy density**	3.0	J/mm^2
			Slant range	274.06	m			

Equivalent Bare Charge	114.531	kg	68.9	**kPa overpressure produced at**		18.6	m
Equivalent weight of TNT	114.531	kg	**Overpressure at**		18.4 m is	71.0	kPa

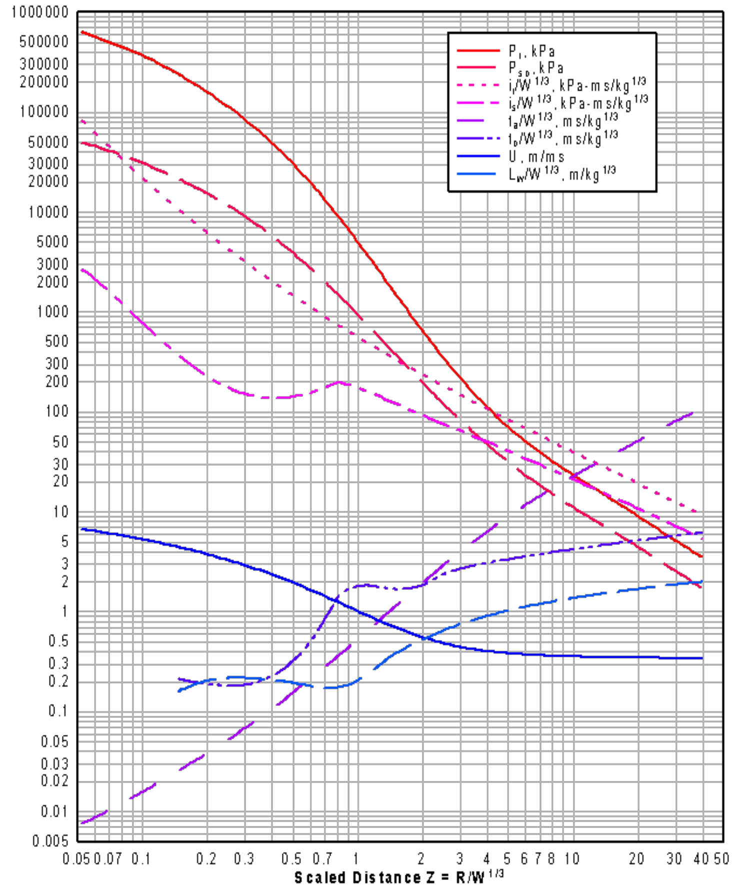

Figure 13: Parameters of positive phase of shock spherical wave of TNT charges from free-air bursts (modified from [9]).

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