

Design and Development of Ultra-Lightweight Personal Body Armor for NIJ Level III++ Protection

H.H.Türkmen¹, M.B.Ünal², K.Kaya³, M.C. Şimşek⁴

¹Nurol Teknoloji Ltd, Oğulbey District. 3060 Street. No.5 06830 Gölbaşı Ankara, Türkiye, huseyin.turkmen@nurolteknoloji.com

²Nurol Teknoloji Ltd, Oğulbey District. 3060 Street. No.5 06830 Gölbaşı Ankara, Türkiye, bartu.unal@nurolteknoloji.com

³Nurol Teknoloji Ltd, Oğulbey District. 3060 Street. No.5 06830 Gölbaşı Ankara, Türkiye, koray.kaya@nurolteknoloji.com

⁴Nurol Teknoloji Ltd, Oğulbey District. 3060 Street. No.5 06830 Gölbaşı Ankara, Türkiye, mert.simsek@nurolteknoloji.com

Abstract. Ceramic body armor has been widely used in military and law enforcement applications due to its excellent ballistic performance. The ballistic performance of a protective armor system comprising Boron carbide – Silicon carbide composite ceramics (Nurol Technology’s special ceramic product) coupled with ultra-high molecular weight polyethylene (UHMWPE) with varying protective levels, crucial research to design the lightest weight of the personal body armor. The ceramic thickness ranges from 2 mm to 3 mm, aiming to optimize impact resistance and energy absorption in personal armor applications. Experimental ballistic tests are conducted to measure impact resistance under controlled conditions, providing insights into the penetration resistance, energy dissipation, and structural integrity of the ceramic-UHMWPE composite when subjected to high-velocity projectiles. To support and be validated with empirical results, LS-DYNA[®] simulations are employed, enabling detailed analysis of the dynamic response of the composite materials under ballistic impact. LS-DYNA[®], a widely used finite element analysis (FEA) software in impact simulations, allows for detailed modeling of material behaviors, including the brittle nature of ceramics and the high tensile strength and toughness of UHMWPE. The simulations account for material heterogeneity, varying ceramic thicknesses, and hardness differences, replicating realistic ballistic impact scenarios.

This research aims to enhance the protection level of ballistic armor while minimizing its weight. It includes an assessment of the correlation between simulated and experimental outcomes, identifying any inconsistencies, and exploring potential causes, such as assumptions or simplifications in the finite element analysis (FEA) model.

Key performance metrics, such as minimum backface deformation, erosion of the ammunition, and overall material integrity, are compared across both methods. This research ultimately seeks to establish the ultimate personal armor solution. By comparing ballistic testing with LS-DYNA[®] simulations, the study aims to refine simulation methodologies and enhance material configurations, contributing valuable insights to the field of ballistic protection and impact resistance.

1. INTRODUCTION

Body armors are specialized equipment designed to protect individuals from various threats. Offering different features such as protection against ballistic, cutting, piercing, and impact threats, body armors vary based on their applications and specific needs [1].

One specific focus in recent studies on body armors involves enhancing ballistic performance using advanced materials and design methodologies. This is particularly significant in addressing the growing demand for lightweight, high-performance protective solutions in various fields, including military and law enforcement applications. The ballistic performance of a protective armor system made of Boron carbide–Silicon carbide ceramic composite materials combined with ultra-high molecular weight polyethylene (UHMWPE) at different protection levels is a challenging study in terminal ballistic literature.

Ballistic ceramics should exhibit high hardness. However, to enhance multi-shot performance, they must also possess improved flexural strength and fracture toughness. In the industry, the reaction-bonding process, which involves metal infiltration into Boron carbide ceramics, is a commonly used method to achieve these properties [2]. However, Nurol Teknoloji's specialized product utilizes a Boron carbide – Silicon carbide composite ceramic instead of metal infiltration. This method notably preserves the high hardness of B4C while significantly enhancing its flexural strength and fracture toughness. At high-velocity impacts, multiple energy absorption mechanisms are involved. These include the

formation of macro-damage areas (e.g., cone cracks and radial cracks), micro-fragmentation zones, and mixed fracture modes [3].

This research prioritizes the development of lightweight ballistic armor with high protection levels. It leverages the finite element modeling approach to achieve this goal. In high-velocity impact scenarios, conducting real-life tests to measure the response of armor materials and predict their behavior is highly challenging, costly, and time-consuming. Thanks to the finite element method, numerous armor solutions can be tested, allowing the structure to be optimized and made more durable [4]. Finite element calculations in this work were conducted using the LS-DYNA[®] commercial software, which provides robust tools for simulating complex ballistic impact scenarios [5].

In this study, key performance indicators such as back-face signature, and overall material performance were evaluated both experimentally and through the finite element model. This study aims to bridge the gap by combining Boron carbide and Silicon carbide properties into a composite armor system, providing both high protection and reduced weight, addressing the challenges in modern armor design.

2. BALLISTIC EXPERIMENT PROCEDURE

2.1. Test Facility and Setup

All ballistic tests were conducted at the certified indoor ballistic shooting range of **Nurol Teknoloji**, by standardized protocols for evaluating the back-face signature (BFS) and penetration performance of armor systems. The shooting experiments were performed under controlled environmental conditions to ensure the repeatability and reliability of the results.



Figure 1: Nurol Teknoloji's Shooting Range.

The final tested armor as shown in Figure 2 assembly comprised a **3 mm thick proprietary NT ceramic** strike-face layer, backed by a **12.5 mm thick high-pressure consolidated ultra-high-molecular-weight polyethylene (UHMWPE)** layer. **The total weight of the final test armor is 1705 g with having areal density 0.25 kg/m² which is significantly lower than comparable commercial products.** The armor plates were produced using standard pressing and sintering parameters provided by the manufacturer to ensure uniformity and quality across all test samples.



Figure 2: Body Armor Plate after the experiment.

The armor samples were rigidly clamped in a vertical position and backed with a calibrated Roma Plastilina No.1 clay block as shown in Figure 3, conditioned to the specifications outlined in NIJ Standard 0101.07, for measuring back-face signature (trauma). Each sample was subjected to a sequence of six shots, conducted at a nominal distance of **15 meters**, which is a standard testing range for personal ballistic protection materials.



Figure 3: BFS measurement setup with P1 plastina.

2.2. Ammunition and Firing Sequence

A total of six ballistic impacts were performed on each armor sample. Three types of ammunition, representative of common ballistic threats encountered in both military and law enforcement scenarios, were used. The firing sequence was standardized across all test samples to ensure comparability:

1. **Two rounds of 5.56×45 mm NATO SS109 (also known as M855)** — a standard military ball round featuring a steel penetrator with striking velocity of 947 - 953 m/s.
2. **Two rounds of 7.62×39 mm MSC (Mild Steel Core)** — a widely used intermediate cartridge associated with AK-pattern rifles with striking velocity of 732 -724 m/s.
3. **Two rounds of 7.62×51 mm NATO M80 Ball** — a full metal jacket round with a lead core, representing a high-energy rifle threat with a striking velocity of 841-855 m/s.

The shots were fired consecutively, with careful targeting to avoid direct overlap while maintaining sufficient spacing to eliminate edge effects and mutual influence between adjacent impact points. Following each ballistic test, X-ray imaging of the body armor plate was conducted to monitor the crack patterns formed on the ceramic layer.

3. NUMERICAL MODELLING

Ballistic impact simulation is a highly complex and non-linear problem. Non-linearity can come from both geometry and material non-linearity. In addition to that, there is excessive large deformation in the materials. All these models and techniques are used in the commercial finite element solver software LS-Dyna[®] for this study.

3.1. Integration-Explicit

In the ballistic impact simulations due to the high number of elements, complex contacts, high-speed dynamics, and very large deformations, explicit time integration is more suitable. In addition to that in terms of computational efficiency explicit time integration calculates the system's future state directly from its current state, making it simple and efficient but conditionally stable, requiring small time steps for accuracy. An explicit scheme can be investigated from Equation 1 for an update of the displacement.

$$u_{t+\Delta t} = u_t + \Delta t \dot{u}_{t+\Delta t} \quad (1)$$

3.2. Contact

Contact algorithm and contact type are other important points in ballistic impact modeling. Although there are several challenges in the implicit algorithm, the explicit scheme is very powerful for the contact algorithms. There are two types of contact that are used in LS-DYNA[®] such as Automatic Surface to Surface Tiebreak and Eroding Single Surface in this paper.

Automatic Surface-to-Surface Tiebreak Contacts are a specialized type of contact used to model the behavior of interfaces that can initially hold two surfaces together but may separate or fail under certain conditions. Its ability to simulate interface failure between similar or different layers under both tensile and shear loading. After the given shear and tensile traction stress limit is exceeded the layers start to separate gradually. Thus, it can be used within the composite structure between the layers of UHMWPE.

Eroding Single Surface Contact refers to a contact definition that allows for interaction between different parts of the same body or mesh (self-contact) and accounts for erosion of elements due to failure criteria. This type of contact is particularly useful in simulations involving severe deformation, fragmentation, or material failure where self-interaction and element deletion are critical aspects. During the definition of this contact type at LS-DYNA[®] choice of the critical erosion, type and its value are too important. After this value reaches the critical limit that element will be deleted.

3.3. Material Models

3.3.1. Johnson-Cook

The Johnson-Cook material model (**MAT_015-JOHNSON_COOK**) in LS-DYNA[®] is widely used for simulating strain- and temperature-dependent plasticity in materials subjected to high strain rates. This model accounts for material softening due to plastic heating and defines flow stress as a function of effective plastic strain, strain rate, and temperature, expressed as:

$$\sigma_y = [A + B\varepsilon_p^n][1 + C \ln(\dot{\varepsilon}^*)][1 - (T^*)^m] \quad (2)$$

where;

$$T^* = \frac{T - T_{ref}}{T_m - T_{ref}}, \text{ and, } \varepsilon^* = \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \quad (3)$$

The coefficients in the equation 2 and equation 3 are stated at the below Table 1.

Table 1: Johnson-Cook Parameter Identification

A	Yield Stress
B	Strain Hardening Coefficient
n	Strain hardening Exponent
ϵ_p	Effective Plastic Strain
$\dot{\epsilon}_p$	Effective Plastic Strain Rate
$\dot{\epsilon}_0$	Reference Strain Rate
C	Strain Rate Coefficient
T_m	Melting Temperature
T_{ref}	Reference Temperature

In terminal ballistic analysis, the Johnson-Cook model is commonly employed to study failure mechanisms in materials like hardened steel cores [6]. The hydrostatic response of materials under these conditions is often modeled using the Mie-Gruneisen equation of state, which relates pressure (p), density (ρ), and internal energy (e), with the Gruneisen parameter (Γ) defined in Equation 4.

$$\Gamma = \frac{1}{\rho} \left(\frac{\delta p}{\delta e} \right)_v \quad (4)$$

The Johnson-Cook Material model are characterized based on the terminal ballistic studies. The parameters of the material model are provided by Table 2.

Table 2: Johnson-Cook Material Parameters for Hardened Steel Core

Part	Material	Model	Source
Core - SS109	Hardened Steel	MAT_015	Weiss et al. (2012) [6]
Core - MSC	Mild Steel	MAT_015	Hála et al. (2024) [7]
Roma Plastina	Clay	MAT_015	Eckhoff et al. (2012) [8]

Analyzing ammunition failure mechanisms is challenging due to the complex interplay of extreme deformation, high strain rates, and elevated temperatures and pressures. Failure criteria are typically based on the maximum effective plastic strain that material elements can endure. When elements reach their critical strain, they are removed from the simulation, providing an efficient computational approach to model material failure. However, this method has limitations, such as ignoring strain rate effects and continuum damage evolution.

3.3.2. Enhanced Composite Damage (MAT_054)

Enhanced Composite Damage Model (**MAT_054-Enhanced_Composite_Damage**) is designed to model laminated composite materials under impact, crash, and dynamic loading conditions. It incorporates an anisotropic constitutive model, progressive failure mechanisms, and element deletion capabilities to capture the behavior of fiber-reinforced composites. The material follows orthotropic elasticity, meaning the stiffness matrix evolves based on damage accumulation. The constitutive relation is depicted in Equation 5.

$$\sigma = D \cdot \epsilon \quad (5)$$

where σ is stress tensor, D is stiffness matrix (updated with damage) and ϵ is strain tensor

The elastic response is defined by Young's moduli (E_A, E_B, E_C), shear moduli (G_{AB}, G_{BC}, G_{CA}), Poisson's ratios ($\nu_{AB}, \nu_{BC}, \nu_{CA}$)

Failure Criteria (Chang-Chang Model): This model differentiates between fiber and matrix failure under tension and compression.

Fiber Failure

1. Tensile failure in fiber direction (DFAILT) in Equation 6:

$$\sigma_{aa} > 0 \Rightarrow e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1, \quad \begin{array}{l} e_f^2 \geq 0 \Rightarrow \text{failed} \\ e_f^2 < 0 \Rightarrow \text{elastic} \end{array} \quad (6)$$

$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0$$

2. Compressive failure in fiber direction (DFAILC) in Equation 7:

$$\sigma_{aa} < 0 \Rightarrow e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1, \quad \begin{array}{l} e_c^2 \geq 0 \Rightarrow \text{failed} \\ e_c^2 < 0 \Rightarrow \text{elastic} \end{array} \quad (7)$$

$$E_a = \nu_{ba} = \nu_{ab} = 0$$

Matrix Failure

1. Tensile failure in matrix direction (DFAILM) in Equation 8:

$$\sigma_{bb} > 0 \Rightarrow e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1, \quad \begin{array}{l} e_m^2 \geq 0 \Rightarrow \text{failed} \\ e_m^2 < 0 \Rightarrow \text{elastic} \end{array} \quad (8)$$

$$E_b = \nu_{ba} = 0 \Rightarrow G_{ab} = 0$$

2. Compressive failure in matrix direction (DFAILM) in Equation 9:

$$\sigma_{bb} < 0 \Rightarrow e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right] \frac{\sigma_{bb}}{Y_c} + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1, \quad \begin{array}{l} e_d^2 \geq 0 \Rightarrow \text{failed} \\ e_d^2 < 0 \Rightarrow \text{elastic} \end{array} \quad (9)$$

$$E_b = \nu_{ba} = \nu_{ab} = 0 \Rightarrow G_{ab} = 0$$

$$X_c = 2Y_c, \text{ for } 50\% \text{ fiber volume}$$

Although the material model defines separate failure criteria, it uses them simultaneously. Since by nature matrix fails initially, the model progressively reduces the effective fiber strength in proportion to the matrix damage accumulates.

3.3.3. Modified Johnson-Cook

The Modified Johnson-Cook model incorporates adiabatic heating into the standard Johnson-Cook material formulation. The stress response for this model is given by Equation 10.

$$\sigma_{eq} = (A + B\varepsilon_{neq}) \left(1 + \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right) (1 - T^m) \quad (10)$$

where A , B , C , n , and m are material parameters as defined in the Johnson-Cook model. Here, ε_p represents the equivalent plastic strain, $\dot{\varepsilon}_p/\dot{\varepsilon}_0$ while denotes the normalized plastic strain rate. The material model used in the analysis are listed in Tables 3 and 4.

Table 3: Modified Johnson-Cook Parameters for Brass

Part	Material	Model	Source
Jacket	Brass	MAT_107	Manes et al. (2020) [9]

Table 4: Modified Johnson-Cook Parameters for Lead

Part	Material	Model	Source
Lead	Lead	MAT_107	Choudary et al.(2020) [10]
Core – M80	Lead	MAT_107	Choudary et al.(2020) [10]

The failure model used in this formulation is based on the Cockcroft-Latham failure criterion, which considers both stress and strain. It is defined by Equation 11:

$$D = \frac{1}{W_{cr}} \int_0^{\epsilon_{eq}} \max(\sigma_1, 0) d\epsilon_{peq} \quad (11)$$

where σ_1 is the maximum principal stress, and W_{cr} represents the Cockcroft-Latham parameter, indicating the total plastic work. According to this failure criterion, material failure occurs when D reaches a value of one. The key differences between the Modified Johnson-Cook model (**MAT_107-MODIFIED MAT_015-JOHNSON_COOK**) and the standard Johnson-Cook model (**MAT_015-JOHNSON_COOK**) lie in strain rate dependency and failure criteria. The Cockcroft-Latham parameter can be determined through a simple uniaxial tensile test, where the area under the stress-strain curve represents the total plastic work.

3.3.4. Johnson-Holmquist-2

The Johnson-Holmquist model (**MAT_110-JOHNSON_HOLMQUIST_CERAMICS**) is designed for brittle materials and incorporates a transition regime between intact and fractured states. It specifically accounts for material strength in both conditions using a pressure-volume relationship that includes the effects of bulging. This model considers damage, pressure, and strength as key factors in material behavior. To simplify the equations, normalization is applied, and the normalized equivalent stress is given in Equation 12 for the intact material [5]:

$$\sigma_i^* = A(P^* + T^*)^N (1 + C \ln \dot{\epsilon}^*) \quad (12)$$

For damaged material, the stress is adjusted based on the level of accumulated damage D , as shown in Equation 13 [5]:

$$\sigma_i^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*) \quad (13)$$

where σ_i^* is the normalized intact equivalent stress, σ_f^* is the normalized fractured stress, and D represents the damage variable, ranging from 0 to 1 [5].

For fully fractured material, the stress follows Equation 14 [5]:

$$\sigma_f^* = B(P^*)^M (1 + C \ln \dot{\epsilon}^*) \quad (14)$$

The damage accumulation leading to fracture is modeled as the sum of incremental equivalent plastic strain over each integration cycle, as given in Equation 16 [5]:

$$D = \sum \frac{\Delta \epsilon_p}{\epsilon_{pf}} \quad (15)$$

where the fracture strain ϵ_{pf} is expressed in Equation 17 as [5]:

$$\epsilon_{pf} = D_1 (P^* + T^*)^{D_2} \quad (15)$$

Here, D_1 and D_2 are material constants, while P^* and T^* represent the normalized pressure and the normalized maximum tensile hydrostatic pressure, respectively.[5]

As plastic deformation progresses, the material undergoes fragmentation, reducing the particle size and softening the structure. When the accumulated damage reaches one, the material fully fractures. Equation 18 describes the bulking phenomenon, where hydrostatic pressure increases due to volumetric strain after fracture. The added internal energy, represented by ΔP , contributes to potential internal energy [5].

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 + \Delta P \quad (17)$$

3.4. Mesh Structure

In this research, there are three types of ammunitions. These are namely;

- 5.56x45 mm M855/SS109
- 7.62x39mm MSC
- 7.62X51mm M80

The cores for all ammunition types are modeled with a hexahedral mesh. However, depending on the shape of the cover or backing (lead), the mesh structure could be either hexahedral or triangular. In addition, the cover always has a triangular mesh structure. The ceramic and UHMWPE are modeled with a hexahedral mesh structure with a size of 0.5 mm.

The size of the mesh varies, the reason for this is based on the convergence test. Thus, these ammunitions were characterized and their verifications were accurate at these mesh sizes.

4. RESULTS

Numerical models play a crucial role in the design of hard body armor by allowing the evaluation of key parameters such as weight, thickness, multi-hit resistance, and penetration status—where partial penetration (PP) indicates successful stoppage of the projectile and complete penetration (CP) indicates full perforation—and back-face signature (BFS) performance. This section aims to examine the effect of the different ammunition threads, and the ceramic composite material (Nurol Technology's specialized product) on BFS through numerical examples. By studying the state-of-the-art computational techniques, the behavior of different ammunition such as 5.56x54 mm SS109, 7.62x39 mm MSC, and 7.62x51 mm M80, ceramic composite material is investigated by comparing real test campaigns. The deformations caused by the 5.56x45 mm SS109 ammunition, which features a hardened steel core, were investigated by examining the BFS. The analysis of the resulting BFS indicates that the performance of such a lightweight plate at this protection level was successfully simulated with a very low margin of error. The BFS values are listed in Table 5 for both numerical and experimental results. The ballistic performance of the armor plate was investigated against 7.62x39 mm MSC (Mild Steel Core) ammunition through the analysis of BFS. The results presented in Table 5, demonstrate the plate's effective performance. These tests were successfully replicated through numerical modeling, confirming the accuracy of the simulation approach. 7.62x51 mm M80 ammunition poses a significant threat to body armor plates, primarily due to the substantial trauma it can inflict. The impact of this threat on the developed product was analyzed with the BFS. According to the results, the M80 threat caused greater trauma compared to other ammunition types; however, in parallel with ballistic test outcomes, the measured BFS values as depicted in Table 5 remained well below the 44 mm threshold based on NIJ 0107.01.

Table 5 summarizes the simulated and experimental BFS depths for each shot. All rounds resulted in partial penetration, defined as the projectile not perforating completely through the armor, yet causing measurable back-face trauma in the backing material. The BFS was measured at the point of maximum clay deformation behind the armor panel immediately after each shot as shown Figure 4.

Table 5: Back-face signature (BFS) depths recorded after each shot.

Shot No.	Ammunition Type	Simulation-BFS (mm)	Experiment-BFS (mm)	Penetration Type
1	5.56x45 mm NATO SS109 (M855)	12 mm	13 mm	Partial Penetration
2	5.56x45 mm NATO SS109 (M855)	11 mm	14 mm	Partial Penetration
3	7.62x39 mm MSC	16 mm	10 mm	Partial Penetration
4	7.62x39 mm MSC	18 mm	14 mm	Partial Penetration

5	7.62×51 mm NATO M80 Ball	28 mm	32 mm	Partial Penetration
6	7.62×51 mm NATO M80 Ball	34 mm	34 mm	Partial Penetration



Figure 4: BFS Marks after the shoot for the proper measurement.

BFS depths for the lighter rounds (5.56x45 mm SS109 and 7.62x39 mm MSC) remained well below the critical threshold of 44 mm based on NIJ 0107.01, suggesting an effective dissipation of kinetic energy through the ceramic and UHMWPE layers. However, as expected, 7.62×51 mm M80 projectiles resulted in significantly higher deformation values, though still within survivable limits. The simulated and experimental BFS results in Table 5 show good overall agreement. For 5.56×45 mm SS109 rounds, differences are minimal (1–3 mm). Simulations slightly overpredict BFS for 7.62×39 mm MSC rounds, with up to 6 mm deviation. For 7.62×51 mm M80 rounds, the results are close, with one exact match. Overall, the simulation reliably reflects experimental trends for partial penetrations. Upon examining the layers of UHMWPE as shown in Figure 5, it was observed that the first 5.56x45 mm SS109 projectile did not penetrate any layers, while the second one was stopped at the sixth layer. The 7.62x39 mm MSC projectile was found to be halted at the thirteenth and fifteenth layers following the layer separation process. The 7.62x51 mm M80 projectile was determined to have been stopped at the seventy seventh and eighty second layers.



Figure 5: The layer of UHMWPE after test

Due to the complete fragmentation and deformation of the 5.56x45 mm SS109 and 7.62x51 mm M80 projectiles after testing, it was not possible to make a quantitative assessment. Only the MSC projectile was recovered from within the plate in a mushroomed shape, as shown in Figure 6. A similar geometry was also observed in the analysis results.



Figure 6: The deformation on the 7.62x39 mm MSC for experiment(a) and simulation(b)

5. CONCLUSION

In this study, the ballistic performance of an ultra-lightweight personal body armor system developed by NuroI Teknoloji was successfully evaluated through both experimental testing and numerical simulations. The results demonstrated that the specialized NT ceramic-UHMWPE composite armor system effectively withstood multiple ballistic threats while consistently maintaining BFS values well below the critical NIJ 0101.07 threshold of 44 mm. A key achievement of this research was the armor's ability to provide high-level ballistic protection without any instance of complete penetration (CP) across all tested ammunition types and impact sequences. The correlation between experimental and simulation results confirms the reliability of the computational models employed and validates their use in future armor development projects. Overall, this research reaffirms NT's commitment to delivering premium, lightweight personal body armor solutions characterized by exceptional ballistic protection, and minimal backface trauma under demanding threat conditions.

6. REFERENCES

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