Experimental Research on Igniting the Aviation Kerosene by W-Zr Reactive Fragment

Kai Liu*, Guitao Liu, Min Chen, Dong Liang, Zhiwei Wang, Wenyan Ge and Delin Li

Inner Mongolia Metal Material Research Institute, Ningbo 315103, China
*Corresponding author: cumt_lk@sina.com

Abstract. Taking W-Zr reactive fragment as the research object, the influence of fragment density, shape and size parameters on the armor-piercing ignition fuel tank was studied through the simulated target test of 12.7mm ballistic gun launch. Combined with high-speed camera, the armor-piercing ignition behavior of the reactive fragment and ignition mechanism were revealed. The results show that the ignition fuel tank with low and medium density activity fragments has better effect, and the ignition speed of the fragments with high density decreases about 26%. The cube shape fragments have the best ignition performance, followed by cylindrical fragments and spherical fragments. The ignition ability of 7mm and 8mm fragments is equivalent, while the ignition ability of 8mm fragments is slightly stronger. The ability of W-Zr fragment to ignite aviation kerosene is closely related to the content of active components and the degree of breakage when it hits the target plate. Under the action of high-speed impact on the target plate, the fragments ware quickly broken into fragments with a certain flying Angle and high temperature combustion. Under the coupling action of the impact kinetic energy of the fragments and the chemical reaction heat, the critical ignition condition of fuel is reached, and the fuel tank is ignited.

1. Introduction
The explosive warhead is a new generation of missile and air bomb, which is mainly dependent on the use of prefabricated broken pieces to achieve multi-function damage, and the active materials (reactive materials) have been a hot spot in the field of high damage areas, with the continuous improvement of battlefield requirements and the upgrading of equipment and materials, and some materials have been applied in the combat department. At present, the domestic research is more mature and the active material that is applied in the model is the zirconium non-crystalline composite material, the active material, the combustion alloy and the tungsten zirconium alloy.
The research of the material of the active materials is relatively small, and the paper studies the influence of the density, shape and size of the film, and the influence of the strength of the combustion aviation kerosene, and the process of the high speed photographic record of the target fuel tank, and the mechanism of the ignition mechanism of the W-Zr reactive fragment, and the experimental data support for the design and breaking of the explosive warhead design and the specification of the broken chip.

2. Experiment

2.1. Target sample test
W-Zr reactive fragment is a kind of active fragments with good comprehensive properties, such as detonation-proof, arm-piercing, ignition and arson, etc. It is prepared by powder metallurgy process, and has been finished in batch production. Different samples were designed according to the test needs. The density of alloy fragments is controlled by adjusting W content, and the size and shape of the fragments are adjusted by mold. According to different density, size and shape, the fragment samples can be divided into 18 cases. The specific specifications and parameters are shown in Table 1. More than 10 active fragments of each specification were prepared for target test, as shown in Figure 1.

| Specification | Density (g·cm⁻³) | Size (mm) | Shape | Specification | Density (g·cm⁻³) | Size (mm) | Shape |
|---------------|------------------|-----------|-------|---------------|------------------|-----------|-------|
| L-7-Q         | 7.2              | φ7        | spherical | L-8-F         | 7.2              | 8×8×8     | cubical |
| M-7-Q         | 10.5             | φ7        | spherical | M-8-F         | 10.5             | 8×8×8     | cubical |
| H-7-Q         | 13.0             | φ7        | spherical | H-8-F         | 13.0             | 8×8×8     | cubical |
| L-8-Q         | 7.2              | φ8        | spherical | L-7-Z         | 7.2              | φ7×7×7    | cylinder |
| M-8-Q         | 10.5             | φ8        | spherical | M-7-Z         | 10.5             | φ7×7     | cylinder |
| H-8-Q         | 13.0             | φ8        | spherical | H-7-Z         | 13.0             | φ7×7     | cylinder |
| L-7-F         | 7.2              | 7×7×7    | cubical  | L-8-Z         | 7.2              | φ8×8     | cylinder |
| M-7-F         | 10.5             | 7×7×7    | cubical  | M-8-Z         | 10.5             | φ8×8     | cylinder |
| H-7-F         | 13.0             | 7×7×7    | cubical  | H-8-Z         | 13.0             | φ8×8     | cylinder |

**Figure 1.** Samples of reactive fragment:

- a cylinder fragments; b cubical fragments; c spherical fragments.

2.2. Target test design
In the test design, a 12.7mm ballistic gun was used to load, and an optical screen target was used to measure the speed of the fragments. The target plate was 6mm thick Q235 steel plate. A fuel tank
containing aviation kerosene was placed 100mm away from the target, with the oil content being about 1/6 of the fuel tank volume. The specific process of the fragmentation hitting the target plate and igniting the fuel tank is recorded by high-speed photography. The target test diagram is shown in Figure 2.

**Figure 2.** Schematic diagram of ballistic experimental setup.

The W-Zr reactive fragments were put into the nylon cartridge and assembled into the test cartridge. After the fragments were out of the chamber, the nylon cartridge fell off automatically. The fragment speed is adjusted by controlling the charge amount of propellant. The different density, different shapes and different size fragment in turn to carry on the target of test, test out the limit of the fragment under the influence of each parameter. The limit speed of ignition is defined as a fragment penetrating the target plate can be reliable ignition fuel tank at the lowest speed, reliable ignition by high-speed photography. By comparing the ultimate ignition speed and fuel tank combustion, the influence of the shape, density and size of the fragments on the ability of the fragments to ignite aviation kerosene was studied.

### 3. Experimental data and analysis

Experiment selected three kinds of density, three kinds of shape and two kinds of size as the research object, study the influence of the fragment to the tank of ignition ability, the influence parameters, combined with a total of 18 different types of fragment target data accuracy, In order to ensure the accuracy of the fragmentation target test data, the fragmentation target test of each specification is more than 3 rounds. The following three parameters, namely density, shape and size, are used to study the impact of the fragmentation ignition fuel tank capacity.

#### 3.1. Study on density impact

The size and shape select 8mm×8mm cylindrical fragmentation, density design three grades, 7.2g/cm³, 10.5g/cm³, and 13.0g/cm³, corresponding to the lower, middle, and high three components in the table below, target test data is shown in Table 2.
Table 2. The influence of density on ignition fuel tank.

| Number | Specification | Speed/m·s⁻¹ | Ignition condition | High speed photographic results                        |
|--------|---------------|-------------|--------------------|--------------------------------------------------------|
| 22#    | L-8-Z         | 805         | Smoking            | A small fire burns and goes out                        |
| 23#    | L-8-Z         | 852         | Small fire burning | The fire continues to burn                             |
| 24#    | L-8-Z         | 724         | Smoking            | A small fire burns and goes out                        |
| 26#    | L-8-Z         | 737         | Smoking            | A small fire burns and goes out                        |
| 27#    | M-8-Z         | 835         | The fire burning   | The fire continues to burn                             |
| 28#    | M-8-Z         | 709         | Smoking            |                                                         |
| 29#    | M-8-Z         | 768         | Smoking            | A small fire burns and goes out                        |
| 30#    | M-8-Z         | 615         | No burning         | No burning                                             |
| 31#    | H-8-Z         | 763         | No burning         | No burning                                             |
| 32#    | H-8-Z         | 933         | No burning         | No burning                                             |
| 40#    | H-8-Z         | 1050        | Smoking            | A small fire burns and goes out                        |

When the fragmentation velocity of low-density W-Zr reactive fragment is about 730m/s, the ignition situation of the fuel tank is smoke. It is observed that the fuel tank is ignited under high-speed photography, and the small fire burns for a short time and then goes out. It can be judged that the ultimate ignition velocity of the low-density fragment is 730m/s. The medium-density fragments failed to ignite the fuel tank at 615m/s, the fuel tank was reliably ignited at 768m/s, and the fuel tank was smoking visually at 709m/s. No images were collected due to fault problems in high-speed photography. However, the ultimate ignition speed of the medium-density W-Zr fragments could be determined to be between 710–770m/s, which was basically equivalent to the low-density alloy fragments. And high-density fragment 1050 m/s speed, high-speed photography to observe ignition, after a small fire extinguishing, to determine the limit of high-density cylindrical W-Zr fragment ignites the rate of 1050 m/s, therefore, low and medium density limit speed of ignition is about 750 m/s, relatively high density activated fragment limit speed reduced by 28%.

3.2. Study on shape influence

The commonly used fragments in the warhead are spherical, cylindrical and cubic shapes. This experiment selects these three commonly used shapes as the research objects to study the influence of shapes on the ability to ignite aviation kerosene. The density and size parameters are fixed. The density is 7.2g/cm³ and the size is 7mm. The target test data are shown in Table 3.

Table 3. The influence of shape on ignition fuel tank.

| Number | Specification | Speed/m·s⁻¹ | Ignition condition | High speed photographic results                        |
|--------|---------------|-------------|--------------------|--------------------------------------------------------|
| 01#    | L-7-Q         | 1031        | No burning         | No burning                                             |
| 17#    | L-7-Q         | 1101        | Smoking            | No burning                                             |
| 07#    | L-7-Z         | 1079        | The fire burning   | The fire continues to burn                             |
| 08#    | L-7-Z         | 899         | Small fire burning | A small fire burns and goes out                        |
| 09#    | L-7-Z         | 737         | Smoking            | A small fire burns and goes out                        |
| 34#    | L-7-F         | 869         | The fire burning   | The fire continues to burn                             |
| 35#    | L-7-F         | 751         | Smoking            | A small fire burns and goes out                        |
| 36#    | L-7-F         | 728         | Small fire burning | A small fire burns and goes out                        |
According to the data in Table 3, there was no ignition tank at the speed of 1031 m/s for spherical fragments of No. 1, and the speed was increased to 1101 m/s (17°), but the fuel tank still failed to ignite. It can be seen that the ultimate ignition tank speed of spherical fragments was above 1100 m/s. The cube fragment is 728 m/s (36°), and the high-speed photography is small fire burning and then goes out. When the cylinder fragment has a speed of 737 m/s, the ignition effect of the tank is smoke, and the high-speed photography observation is short time ignition and goes out. It can be judged that the ultimate ignition speed of the cube fragment is the same as that of the cylinder fragment, which is about 730 m/s. At the same time, by comparing the data of 7° (cylinder) and 34° (cube), the ignition effect is big fire and keeps burning, but the cylinder fragmentation speed is 1079 m/s, while the cube fragmentation speed is only 869 m/s, 200 m/s lower than the cylinder fragmentation speed. Based on the effect of three kinds of splintered ignition oil tank, we can know the ignition ability: cubic > cylindrical > ball. The effect diagram of the fragmentation ignition tank is shown in Figure 3, in which 3-a is the ignition and the fire continues to burn; 3-b for ignition, after a small fire goes out; 3-c is smoke.

![Image](https://via.placeholder.com/150)

Figure 3. The picture of fuel tank ignited by reactive fragment

### 3.3. Study on size influence

Warhead preformed fragment size considering two aspects, one is broken after the warheads detonation slice of uniform density and scope, another is the size of the fragment after arriving at the target damage effect, balance the two aspects of preformed fragment size generally is 6 ~ 10 mm, 7 mm and 8 mm two dimensions used most, this experiment mainly study the two size of 7 mm, 8 mm fragment ignition fuel tank capacity, the influence of the selection of density in the ignition ability, two kinds of low density, shape selection of ignition ability good cube fragment with cylindrical fragment. The specific target test data are shown in Table 4.

| Number | Specification | Speed/m·s⁻¹ | Ignition condition | High speed photographic results |
|--------|---------------|-------------|--------------------|---------------------------------|
| 34°    | L-7-F         | 869         | The fire burning   | The fire continues to burn      |
| 35°    | L-7-F         | 751         | Smoking            | A small fire burns and goes out |
| 36°    | L-7-F         | 728         | Small fire burning | A small fire burns and goes out |
| 37°    | L-8-F         | 846         | The fire burning   | The fire continues to burn      |
| 38°    | L-8-F         | 704         | No burning         | A small fire burns and goes out |
| 39°    | L-8-F         | 735         | Small fire burning | A small fire burns and goes out |
| 11°    | M-7-Z         | 873         | Smoking            | A small fire burns and goes out |
| 12°    | M-7-Z         | 813         | Smoking            | A small fire burns and goes out |
First of all, two sizes of low-density cube fragmentation ignition tanks (34# ~ 39#) are compared. According to the data in the above table, the ultimate ignition speeds of L-7-F and L-8-F fragmentation are 728m/s and 735m/s respectively, with little difference in ultimate ignition speeds. By comparing the data of 34# and 37#, the fragmentation velocity was 869m/s and 846m/s respectively, and the ignition was ignition and fire continued burning. It can be seen that there is little difference in ignition ability between the two sizes of low-density cube fragments. To contrast medium density, ignition ability difference between two cylindrical fragment size and contrast 11# and 27# ignition conditions, the size of 8 mm medium density ignition cylindrical fragment is better than that of 7 mm fragment, compared to data of 29 # and 12 # , shows the limit ignites speed of 7 mm cylindrical fragment is about 810 m/s, 8 mm fragment ignition limit speed is about 760 m/s. The limit ignition rate of the 8mm medium density cylindrical fragmentation is 5% lower than that of 7mm. Combined with the effect of low-density cube fragmentation and medium-density cylindrical fragmentation ignition tank, it can be seen that 8mm fragmentation has a slight advantage over 7mm fragmentation in ignition tank capability.

4. Ignition Mechanism

4.1. Armor-piercing ignition behavior

The behavior of reactive fragments hitting the target plate can be summarized into two stages: the first stage is the process of penetrating the target and penetrating the fuel tank; the second stage is the process of igniting the fuel tank. There is a distinct sequence between the two stages. The first stage is short, on the order of a few milliseconds, but plays a decisive role in the whole process of armor-piercing and igniting the tank. The second stage fuel tank burns for tens of millimeters to several minutes [5,6].

The first stage penetrates the target and penetrates the fuel tank process. At the moment when the fragments hit the target plate, a few fragments splash back. As shown in Figure 4-B, most of the fragments penetrated through the target plate and then through the fuel tank. In the process of penetrating the steel plate, the fragmentation is firstly subjected to the compressive stress of high strain rate, and the compressive stress is released rapidly after passing the target. In the process of extruding and releasing, the fragmentation is broken into small granular fragmentation clouds. In the process of penetrating the fuel tank behind the target, the pore expansion effect is formed on the front and rear walls of the fuel tank. In the process of penetrating the steel plate, the reactive fragments undergo oxidation reaction under the effect of high-speed friction, releasing a large amount of heat, the temperature can reach up to thousands of degrees, and forming the ignition source of high-speed flight, as shown in The flash point in Figures 4-a/b/c process is shown in Figure 4 during the process of penetrating the target and the fuel tank.

Second stage ignition tank process. In the process of penetrating the fuel tank, the high-speed fragmentation cloud after passing through the steel plate violently agitates the fuel inside the fuel tank under the effect of impact and fragmentation cloud, making the fuel and air rapidly mix to form
inflammable and explosive mixture of oil and gas (hydrocarbon gas). At the same time, the temperature in the fuel tank rises rapidly, and part of the oil and gas mixture is ejected out of the fuel tank along with the fragmentation cloud. The broken cloud after passing the steel plate interacts with the oil and gas mixture in the fuel tank during high-speed flight. Under the coupling effect of impact kinetic energy and chemical reaction heat release, the fuel ignition condition is reached, and the fuel tank is ignited. The process stage of ignition tank is depicted in Figure 4.

![Figure 4](image_url)

**Figure 4.** High-speed photography of reactive fragment piercing armor and igniting aviation kerosene.

### 4.2. Ignition mechanism

Due to its fragile nature, W-Zr reactive fragments are quickly broken into high temperature burning fragments with a certain flying angle after hitting the target plate. This fragmentation cloud violently agitates the fuel inside the tank, causing the fuel and air to rapidly mix to form flammable and explosive mixture of oil and gas (hydrocarbon gas). During the violent agitation, the fragmentation cloud and the oil and gas mixture exchange sufficient energy. At the same time, the W-Zr reactive fragmentation cloud reacts and burns immediately after hitting the target plate. After combustion, the fragmentation cloud releases a large amount of heat energy, which is equivalent to a large number of ignition sources, and realizes multi-ignition for the oil and gas mixture. The jet fuel is ignited by the
impact of the fragmentation cloud and the coupling effect of the combustion heat, and the fire continues to burn.

Whether aviation kerosene fuel tank can be ignited also depends on the fuel ignition criterion. Johnson et al. obtained the ignition criterion of aviation kerosene by studying the ignition behavior of aviation kerosene on hot material surface [7].

\[ t = A \cdot \exp \left( \frac{E}{RT} \right) \cdot P^{-n} \]

Where, \( T \) is the ignition delay time, \( A \) is the pre-exponential factor, \( E \) is the activation energy, \( P \) is the pressure, \( R \) is the gas constant, \( T \) is the temperature, \( n \) is the reaction level.

For common aviation kerosene, pre-exponential factor \( A=1.68 \times 10^{-6} \text{ms} \cdot \text{atm}^{-2} \), activation energy \( E=37.78 \text{kcal/mol} \), reaction level \( n=2 \). Critical ignition conditions of aviation kerosene are obtained, as shown in Figure 5. As can be seen from the figure, the ignition behavior of aviation kerosene depends on the fuel temperature and its duration. The higher the temperature, the longer the ignition delay, and the higher the probability of the fuel being ignited.

![Figure 5. Critical ignition conditions of aviation kerosene.](image)

W-Zr reactive fragment is mainly composed of high-density component W and reactive component Zr. The fragmentation density depends on the ratio of the two components. Combined with the effects of three kinds of density-active fragmentation ignition tanks, the ignition capacity of high-density alloy fragmentation is significantly lower than that of medium-density and low-density alloy fragmentation. High density activated fragment yuan of active components in quality than just 20%, after hitting the target board broken cloud particles formed due to the less active component, the target response of cloud amount less, equivalent to the ignition delay time is short, and because of less active ingredients, chemical reaction temperature is low, cannot reach critical ignition condition of the fuel, so difficult ignition fuel tank.

The shape of the fragment has a great influence on the ignition tank. The main reason is that the fragmentation of different shapes fragments after penetrating the target is different. The spherical fragments are mainly in point contact at the moment of impact on the target plate, and the compression stress is uniformly distributed during the process of crossing the target. After unloading, the fragmentation degree is far less than that of cube and column fragments. Cube fragments are more
likely to be broken when they hit the target plate because of their polygonal characteristics. The smaller the fragments, the more the number of fragments, which is equivalent to the longer ignition delay time. The smaller the debris, the more likely it is to burn after impact, and the more complete the chemical reaction, release energy, and ignition temperature. When the ignition temperature and ignition time are favorable, the fuel tank is more likely to be ignited. Compared with cube, cylindrical fragments have fewer edges and corners, but more than spherical fragments, and their ignition ability is better than ball and weaker than cube. Compared with cube and cylinder, spherical fragments are less fragileness, lower ignition temperature and ignition delay time, and their ignition ability is poor.

From two dimensions of 7 mm to 8 mm, W-Zr reactive fragment size difference is not obvious influence on ignition ability for both in terms of size, same shape under the same density, the content of reactive components and fragmental fragmentation is consistent, the difference is that after the broken cloud amount, and 7 mm fragment size for 6 mmQ235 steel plate, the broken fragments number after penetrating the target has reached the minimum threshold, the ignition fuel tank in this case, the two dimensional fragment ignition ability difference, from 7 mm to 8 mm fragment broken ignition fuel tank capacity slightly some advantage, but the advantage is not obvious, is consistent with the test results.

5. Conclusions
Taking W-Zr reactive fragments as the research object, the influence of fragmentation density, shape and size on the ability of active fragmentation ignition tank was studied, and the ignition mechanism was explored, and the following conclusions were drawn:

1) The ability of W-Zr reactive fragments to ignite aviation kerosene is closely related to the content of the active components of the fragments and the fragmentation property when it hits the target plate. The effect of low and medium density reactive fragmentation ignition tank is better, and the ignition speed is about 26% lower than that of high-density fragmentation.

2) The shape of fragments has a great influence on the ignition capability, mainly through the degree of fragmentation after the fragments hit the target plate. The cube shape fragments have the best fragmentation and the strongest ignition capability, followed by cylindrical fragments and spherical fragments with the worst comparison.

3) The size has a certain influence on the ignition tank capacity of fragments. 8mm fragments have a certain advantage over 7mm fragments, but the advantage is not obvious.

4) Under the action of high-speed impact on the target plate, the reactive fragment is quickly broken into a fragment cloud with a certain flight Angle and high temperature combustion. Under the coupling effect of the impact kinetic energy of the fragment cloud and the reaction heat, the critical ignition condition of fuel is reached, and the fuel tank is ignited.

6. References
[1] Wang Zhubo, Zhao Feng, Xie Jin, et al Numerical Simulation on Effect of Velocity of Different Shape Tungsten Fragments Penetrating Armor Plate Ordnance Industry Automation, 2015,34(2):53~55

[2] WANG Haifu, ZHENG Yuanfeng, YU Qing-bo, et al. Experimental research on igniting the aviation kerosene by reactive fragment Acta Armamentarii, 2012, 33(9), 1148~1152
[3] Kong Xiangshao, Wu Weiguo, Du Zhipeng, et al. Research On Fragments Characteristic Of Cylindrical Warhead[J]. *Engineering Mechanics*, 2014, 31(1): 243～249

[4] Xu Huazhen, Li Xiangdong, The Igniting Damage Effect of Energetic Fragments on Diesel Oil Box. *Journal of Projectiles, Rockets, Missiles and Guidance*, 2012, 32(2): 8588

[5] XIAO Yan-wen, Research on Penetration-induced Blast Effect and Damage Mechanism of Reactive Material Fragment Beijing: School of Mechatronic Engineering Beijing Institute of Technology

[6] LIU Xiao-jun, Research of Mechanical Behavior and Impact-Induced Reaction Mechanism for Reactive Materials Beijing: School of Mechatronic Engineering Beijing Institute of Technology

[7] Johnson A. M, Roth A. J, Moussa N.A. *Hot surface ignition tests of aircraft fluids* Technical report AFWAL-TR-88-2101, Wright-Patterson AFB, 1988.

[8] CHEN Jin, YUAN Bao-hui, LIANG Zheng-feng et al. An Experimental Evaluation Method of Energy Release Characteristics of Reactive Material *Chinese Journal of Explosives & Propellant*. 2015, 38(3): 49～53