Safety Analysis of THAAD Anti-Missile System Launcher

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Abstract: Safety analysis is a very important link in the assessment of damage effect before combat operations, and it is also the premise of war damage assessment of weapon targets. This paper takes the launcher of THAAD anti-missile system as the research object, analyzes the structure and functional characteristics of the launcher of THAAD anti-missile system based on literature, reconstructs the three-dimensional model of the launcher, classifies its damage grade, and defines the key vulnerable parts of the launcher. Taking the fragment detonation warhead as an example, the failure mode and damage grade of the key vulnerable parts under the action of fragments are analyzed, and the K and F damage tree models of the launcher of the THAAD anti-missile system are constructed, which provide reference for the security evaluation and research of the THAAD anti-missile system.

1. Introduction
The US missile defense system[1] consists of the "Aegis" anti-missile system, the "land-based mid-range defense" system, the THAAD system, the "Patriot" system, airborne laser weapons, and the extended "medium-range air defense" system. Among them, the THAAD anti-missile system is the most important part of the U.S. terminal missile defense system. It not only has good defensive performance, but also has strong offensive properties, and can form a land and sea double-layer anti-missile network together with the Aegis ship and the "Patriot-3" missile. Therefore, the research on the safety of the THAAD anti-missile system is of far-reaching significance.

For the study of the THAAD anti-missile system, Liu Qian[2] and others introduced the combat characteristics of the THAAD anti-missile system as a whole, and summarized and analyzed its advantages and threats[3]; Sun Chao[4] and others introduced the technical and tactical performance and deployment of the THAAD anti-missile system, and explained it clearly from a strategic perspective; Zhao Hui[5] compared the THAAD anti-missile system with the "Patriot-3" For comparison, it focuses on the unique KKV killing technology of THAAD: A kinetic energy killer composed of a seeker, a guidance device and an attitude control orbit control system. Predecessors' research mainly focused on the overall overview of the THAAD anti-missile system's technical and tactical indicators, operational characteristics, and deployment, while studies on the THAAD anti-missile system structure, functional characteristics, and security have not been reported in the news.

Scholars have done a lot of work on the safety research of launch vehicles. Dai Haifeng[6] relied on computer simulation technology to simulate the damage of the missile launch vehicle, and improved the calculation effect of the precision guided weapon's damage ability to the missile launch vehicle; Xu...
Yusheng [7] used ray tracing method to analyze the target characteristics of the launch vehicle, to improve the identification and anti-stealth capabilities of this missile system; Yang Shiron [8] for a certain type of missile launcher, based on the functional characteristics of different mission stages to classify the damage level, and use the damage tree method to analyze the key vulnerable parts of the launch system. It provides a set of effective analysis methods for the safety evaluation of launch vehicles.

Aiming at the specific target THAAD anti-missile system launch vehicle, this paper adopts the damage tree method to analyze the structure and functional characteristics of the THAAD anti-missile system launch vehicle, classify the damage level of the launch vehicle, and reconstruct the three-dimensional model of the launch vehicle. Define the key vulnerable parts of the launch vehicle. Taking the fragment killing warhead as an example, the failure mode of each key vulnerable component under the action of fragments is analyzed, and the damage model of the THAAD anti-missile system launch vehicle K-class and F-class is finally constructed.

2. Analysis of the structure and function of the THAAD anti-missile system launch vehicle

2.1. Structural analysis

The THAAD anti-missile system launch vehicle is composed of various components, and its various functions are also produced through the coordination of the corresponding physical components. Therefore, to study the target safety of a missile launch vehicle, it is necessary to analyze its structure first, which is an important part of the safety analysis of the THAAD anti-missile system.

The THAAD anti-missile system launch vehicle is composed of a modified container loading system storage vehicle [9], supplemented by a whole ammunition storage and transportation box, and an electronic equipment module. The total length of the vehicle is 1455cm, the width is 240cm, the height of the front vehicle is 255cm, and the height of the rear vehicle is 305cm. The schematic diagram of the structure is shown in Figure 1.

![Figure 1 Schematic diagram of the THAAD anti-missile system launch vehicle](image)

Among them, the main components of the storage truck are the frame, the cockpit, the engine, the tire, the fuel tank and the hydraulic cylinder. The storage box contains the launch tube and the missile. The electronic equipment module mainly includes power supply boxes, power distribution devices, substations, relays, contactors and other components.

Based on the main structure of the THAAD anti-missile system launch vehicle, reconstruct its three-dimensional model, as shown in Figure 2.

![Figure 2 Three-dimensional model of the THAAD anti-missile system launch vehicle](image)

As shown in Figure 2, 1 is the frame, which is located under the storage box, with a total length of 1140cm and a width of 240cm. It plays the role of carrying the storage box and has a small exposed area; 2 is the cockpit, which is located at the head of the body. Its section is 165cm in length, 240cm in width, and 175cm in height, with a large exposed area; 3 is the engine, which is located at the bottom of the cockpit, and the thickness of the engine cover is 1cm, with almost no exposed area; 4 is the tire, which is located at the bottom of the vehicle body, its outer diameter is 135cm, width is 38cm, and its
Figure 2 Three-dimensional model of "THAAD" anti-missile system launch vehicle

exposed area is larger; 5 is a cylindrical fuel tank, which is located on the side of the vehicle body, its outer diameter is 68cm, its length is 142cm, and its thickness is 2mm. The exposed area is large; 6 is a cylindrical hydraulic oil cylinder, which is located under the storage and transportation box. Its outer diameter is 160mm, inner diameter is 90mm, wall thickness is 35mm, and the exposed area is small; 7 is the whole ammunition storage box, which contains the launch tube and missile. It is located at the rear of the car body, with a large exposed area; 8 is the electronic equipment module, which contains the power supply box, power distribution device, transformer device, relay, contactor, etc., it is located between the cockpit and the storage box, there are larger exposed area, as shown in Figure 2b. THAAD anti-missile system launch vehicle storage vehicle is composed of 1~6 together.

Based on the analysis of the main structure of the launch vehicle, the structure frame of the launch vehicle is given, as shown in Figure 3.

Figure 3 THAAD anti-missile system launch vehicle structure frame diagram

2.2. Function analysis

The complexity of the launch vehicle's structure determines the diversity of its functions. The THAAD anti-missile system launch vehicle contains many functional systems, and different functional systems are composed of different sub-functional systems and components. Due to the different layouts of internal mechanisms and equipment of different types of vehicles, and even the external structures, the division of subsystems is not the same, but many common points can still be found. After sorting out and analyzing the literature, the functional system of the THAAD anti-missile system launch vehicle can be divided into three items: motion system, launch system, and electrical system. The functions are as follows:
Motion system: It is an important guarantee for the timely completion of combat tasks after receiving instructions from superiors, and is the most important structural part of the entire vehicle. It mainly completes tasks such as missile reprinting, missile transportation and maneuver marching. It contains the cockpit, engine, fuel tank, and tires. The cockpit can protect the driver from completing maneuvering tasks. The fuel tank provides raw materials for the launch vehicle's mobile march. The engine converts the raw materials provided by the fuel tank into power. The tires can improve the launch vehicle's traction, braking and passing properties, ensuring the launch vehicle's mobility performance.

Launching system: As the core part of the missile launching vehicle, it mainly completes the missile storage, erection, aiming and launching tasks. It contains hydraulic cylinders, launch tubes, and missiles. The hydraulic oil cylinder provides power for the erection of the missile, and the launch tube plays a role of protection and stabilization before the missile is launched. The missile is an important guarantee for the long-range strike capability and the main source of damage capability. Usually anti-missile missiles are damaged by fragments of high-energy explosives, and the fragments produced by the explosion are used to destroy the target missile or warhead, but this method generally cannot achieve the effect of complete destruction. The THAAD anti-missile system uses KKV's kinetic energy kill technology, which can hit the target warhead at high speed, thereby detonating the warhead, and the high heat generated by its high-speed impact can even make the biochemical warfare agent ineffective.

Electrical system: It is the guarantee system of the launch vehicle, which provides power support for other devices and provides a source of power for the erection of the missile. It includes power supply boxes, power distribution devices, substations, relays, and contactors. These five components play the role of powering and distributing the launch vehicle. The functional framework is shown in Figure 4.

3. Safety analysis of THAAD anti-missile system launch vehicle

3.1. Classification of damage levels
Since the THAAD anti-missile system launch vehicle is a lightly armored target, its damage level is mainly considered from its functionality and field maneuverability after the vehicle is damaged.

![Figure 4](image)

Figure 4 THAAD anti-missile system launch vehicle functional framework diagram

When the vehicle is basically destroyed and the launching function and movement function of the launching vehicle have been disabled, the most serious damage level is reached.

When the launch function fails, the launch mission cannot be completed, or the movement function fails, and the launch mission cannot be rushed to the scheduled area in time, but the car body is not completely destroyed, it reaches the next level of damage.

When the movement function fails, but the launch vehicle has arrived at the predetermined area, the failure of the movement function will not affect the ability to perform the launch mission, or the movement function is partially damaged and the launch mission can still be completed, and the damage level is reached again.

When the launch vehicle is hit, but the launch function and movement function are basically intact, and the launch mission can be successfully completed, then this is the lowest damage level.
With reference to the domestic and foreign experience in the classification of armored vehicle damage levels [10], the damage levels of the THAAD missile launch vehicle are divided into four levels: K, F, M, and B:

K: This level means that the entire vehicle has been completely or basically damaged, it is impossible to complete repair work on the battlefield, the structure is completely destroyed, and the combat function is completely lost.

F: This level indicates that the main combat function of the vehicle has been damaged and the launch mission cannot be completed in time. For example, the launching function of the launch vehicle fails and cannot be repaired in a short time.

M: This level indicates that the launch function of the vehicle is normal after being attacked, but the movement function is completely or partially lost, such as a fuel tank leak. But the launch vehicle has arrived or can insist on reaching the scheduled launch site, and the launch mission can be completed.

B: This level means that the vehicle basically retains combat functions after being attacked. For example, the frame is damaged, but the launch mission can still be completed.

3.2. Identification of key vulnerable parts

In military operations, the anti-explosive warhead is usually used to strike the launch vehicle. The main damage elements of the anti-explosive warhead are shock waves and fragments. First, analyze the impact of the shock wave on the launch vehicle. Assuming that the charge mass of a certain anti-explosive warhead is $M=200$ kg, and the distance between the launch vehicle and the explosion center is $R=50$ m, then the overpressure of the anti-explosive warhead explosion shock wave $\Delta P$ on the launch vehicle can be Baker [11] formula for calculation:

$$\Delta P = \frac{0.067}{Z} + \frac{0.301}{Z^2} + \frac{0.431}{Z^3} \quad 0.5 < Z < 70.9$$

(1)

Among them, $Z$ is the contrast distance, $Z = RM^{−1/3}$. It is easy to get $\Delta P = 0.0126$ MPa, and when $\Delta P = 0.035$~0.3 MPa, it will cause varying degrees of damage to the vehicle. At this time, it is far from reaching the standard for destroying the vehicle. Therefore, only the damage to the launch vehicle can be considered.

As mentioned in 1.1 of this article, the missile launch vehicle is composed of three parts: a container loading system storage and transportation vehicle, a whole ammunition storage box, and an electronic equipment module. The damage of any one of the five components of the power supply box, power distribution device, substation, relay, and contactor in the electronic equipment module will cause the function of the electronic equipment module to fail and cause insufficient power supply. However, because the entire THAAD anti-missile system is equipped with a power supply vehicle, which can be used as a backup power supply for vehicles in the anti-missile system, the damage of the electronic equipment module will not cause the launch vehicle to lose its combat function. So only the storage truck and storage box are considered.

In the storage truck:

The surface of the frame will be deformed after being hit by fragments, but it will not affect the combat function of the whole vehicle;

If the cockpit is penetrated by fragments, not only the equipment in the cabin will be damaged, but the driver will also suffer casualties and fail to complete the launch mission;

After the engine is broken down by fragments, the vehicle loses its ability to maneuver. If the launch vehicle has reached the predetermined area, the launch function will not be affected. If it does not reach the predetermined area, the launch mission cannot be completed;

If the fuel tank is broken down by fragments, oil leakage will occur at a low level, which will greatly reduce the distance of the launch vehicle. If the launch vehicle has reached the predetermined area, the launch function will not be affected. If it does not reach the predetermined area, the launch mission cannot be completed. In severe cases, it will explode or burn, and the launch vehicle will be damaged;

Breakdown of the hydraulic cylinder by fragments will cause the erection arm to fail to work normally, causing the launch function to fail;
After the tire is broken down by fragments, the vehicle will also lose its ability to maneuver. If the launch vehicle has reached the predetermined area, the launch function will not be affected. If it does not reach the predetermined area, the launch mission cannot be completed.

In the storage box:

The breakdown of the launch tube will threaten the internal missile and cause the launch function to fail;

If the missile is broken down, the launch function will inevitably fail. Because there are propellant and warhead inside the missile, if the two parts are ignited after being hit by fragments, it is very easy to cause the vehicle to explode or burn, and the launch vehicle will be damaged.

Table 1  Failure modes and damage levels of key vulnerable components

| Part                  | Failure mode                                      | Impact on launch vehicle after failure                                                                 | Damage level |
|-----------------------|---------------------------------------------------|--------------------------------------------------------------------------------------------------------|--------------|
| Cockpit               | Breakdown                                         | The driving equipment is damaged and the launch vehicle cannot complete the launch mission               | F            |
|                       |                                                   | The driver was injured or killed and the launch vehicle could not complete the launch mission           |              |
| Engine                | Breakdown(The launch vehicle did not reach the intended area) | The launch vehicle loses its athletic ability and cannot complete the launch mission                     | F            |
|                       | Breakdown(The launch vehicle has arrived at the intended area) | The launch vehicle loses its athletic ability, but can complete the launch mission                      | M            |
| Tank                  | Explosion/Burn                                     | The launch vehicle was damaged, unable to complete the launch mission                                   | K            |
|                       | Breakdown(The launch vehicle did not reach the intended area) | The launch vehicle loses its athletic ability and cannot complete the launch mission                     | F            |
|                       | Breakdown(The launch vehicle has arrived or can insist on reaching the predetermined area) | The launch vehicle loses its athletic ability, but can complete the launch mission                      | M            |
| Tire                  | Breakdown(The launch vehicle did not reach the intended area) | The launch vehicle loses its athletic ability and cannot complete the launch mission                     | F            |
|                       | Breakdown(The launch vehicle has arrived at the intended area) | The launch vehicle loses its athletic ability, but can complete the launch mission                      | M            |
| Hydraulic cylinder    | Breakdown                                         | The launching function of the launch vehicle is invalid, unable to complete the launch mission         | F            |
| Launch tube           | Breakdown                                         | The launching function of the launch vehicle is invalid, unable to complete the launch mission         | F            |
| Missile               | Explosion/Burn                                     | The launch vehicle was damaged, unable to complete the launch mission                                   | K            |
|                       | Breakdown                                         | The launching function of the launch vehicle is invalid, unable to complete the launch mission         | F            |

For the THAAD anti-missile system launch vehicle, once damaged, it will immediately affect the complete function of the vehicle is the key vulnerable components. After analysis, it can be seen that the cockpit, engine, fuel tank, hydraulic cylinder, tire, launch tube, and missile is a key vulnerable part of the launch vehicle.
This article will determine the key vulnerable parts based on the situation after the parts are damaged by fragments\[^{12}\], combined with the results of the above-mentioned functional analysis. The failure mode and damage level analysis are shown in Table 1.

### 3.3. Establishment of damage tree model

Under the determined damage mode and damage level, analyze the internal connection between the bottom structural damage and the top functional damage of the target or vulnerable component to establish a damage tree, which is an important research method for research about the correlation between the structural damage and functional failure of the target or vulnerable component. In the process of drawing the damage tree, the target can be divided into several functional systems according to different combat functions, and then further divided according to the key components of the functional system. The top event of the damage tree corresponds to a certain level of damage to the target, the intermediate event corresponds to the damage of each functional system, and the bottom event is the root cause event of a certain level of damage to the target due to component damage. Connecting top events, intermediate events, and bottom events through appropriate logic gates can effectively analyze the damage effects of target functional systems and components to determine the vulnerable components of the target, and more intuitively reflect the root cause of the target damage.

Through the analysis of Table 1, it can be obtained that the storage truck and the storage box are in a logical or relationship, and the electronic equipment module does not constitute a logical relationship with these two structures.

In a storage truck, damage to any one of the cockpit, fuel tank, hydraulic cylinder, engine and tires will cause damage and mission delays, and even cause casualties and complete vehicle function damage. Therefore, they are in a logical or relationship. Damage to the frame has no effect on the launch function, and does not constitute a logical relationship with other components.

The damage of the launch tube in the storage and transportation box may cause the damage of the missile, so they are in a logical or relationship.

Through the above analysis, the damage tree model of the K-level and F-level damage of the THAAD anti-missile launch vehicle launch system is established, as shown in Figure 5 and Figure 6.

![Damage Tree Diagram](image)

**Figure 5** THAAD anti-missile system launch vehicle F-level damage tree
4. Conclusions

This article takes the THAAD anti-missile system launch vehicle as the research object, reconstructs the three-dimensional model of the launch vehicle, analyzes its safety based on the structure and functional characteristics of the launch vehicle, and draws the following conclusions:

1. The main structure of the THAAD anti-missile system launch vehicle can be divided into three parts: container loading system storage vehicle, whole ammunition storage box, and electronic equipment module. Its functional system consists of three parts: motion system, launch system, and electrical system.

2. The key vulnerable parts of the THAAD anti-missile system launch vehicle are identified: cockpit, engine, fuel tank, hydraulic cylinder, tire, launch tube, and missile.

3. The explosion or combustion of fuel tanks and missiles will cause damage to the K-class launch vehicle of the THAAD anti-missile system.

4. The breakdown of the cockpit, fuel tank, hydraulic cylinder, engine, tire, launch tube, and missile will cause the F-class damage to the THAAD anti-missile system launch vehicle.

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