Research paper

Study on controlled detonation chamber system of chemical weapons (II): Implosion and sequential detonation

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Abstract
As a destruction method of chemical weapons, the controlled detonation system named DA VINCH was developed. To reduce the damage of the chamber, the detonation is controlled by using 1) implosion process, 2) emulsion explosive as donor charge, 3) sequential multi detonation etc. The effect has been confirmed through the actual destruction of more than 1,000 chemical weapons at Kanda.

Keywords: Controlled detonation, Chemical weapons, Detonation chamber, Donor charge, Sequential multi detonation

1. Introduction
In the first paper [1], the outline of development, design, manufacturing and operation of detonation system named DA VINCH (the Detonation of Ammunition in Vacuum INtegrated CHamber) for destruction of chemical weapons were discussed. In the previous paper, the authors came to a conclusion that the reliability and safety of total system of detonation process depends greatly upon the procedure of detonation itself as well as soundness of hardware.

In the 2nd paper, the authors focus on a study on optimization of detonation. The authors discuss an implosion process; selection of suitable type of donor charge; composition of detonation chains and a procedure of multi detonations at single shot, based on our experiences in the destruction of more than a thousand chemical weapons in hundreds of shots.

2. Implosion process
2.1 Detonation target with high explosives
Figure 1 shows typical cross-sections of chemical bombs found at Kanda Port area.

Every weapon has a booster and a burster which are mainly composed of picric acid, TNT, RDX, naphthalene, or mixture of them. Figure 2 shows burster tubes of 50 kg yellow bombs with picric acid, the color of which is yellow.

The detonation should be controlled properly to ignite a booster and a burster which can possibly be degraded or deteriorated in long years. Fragment speed and its size should also be controlled to minimize the damage to the detonation chamber when the burster is still fully active.

2.2 Implosion
Implosion is the first and necessary process to weaken the impact of fragment generated in the burster explosion. The impact is reduced by putting sufficient donor charge around a munition. Figure 3 is a schematic representation of detonation wave propagation with a 15 kg simulated red bomb. Figure 3 is given under the following conditions.

1) Detonation velocities of Sheet Explosive (SEP) [2], ANFO [3], Picric Acid and TNT 15 %-Naphthalene should be 6.2 km s^{-1}, 3.0 km s^{-1}, 6.3 km s^{-1} and 6.2 km s^{-1}, respectively.
2) The Shock Wave Velocity here is obtained by the Rankin-Hugoniot (R-H) curve for iron [4] in the Pressure-Shock Wave Velocity Plane and the pressure which is given by the intersection of the ANFO KHT

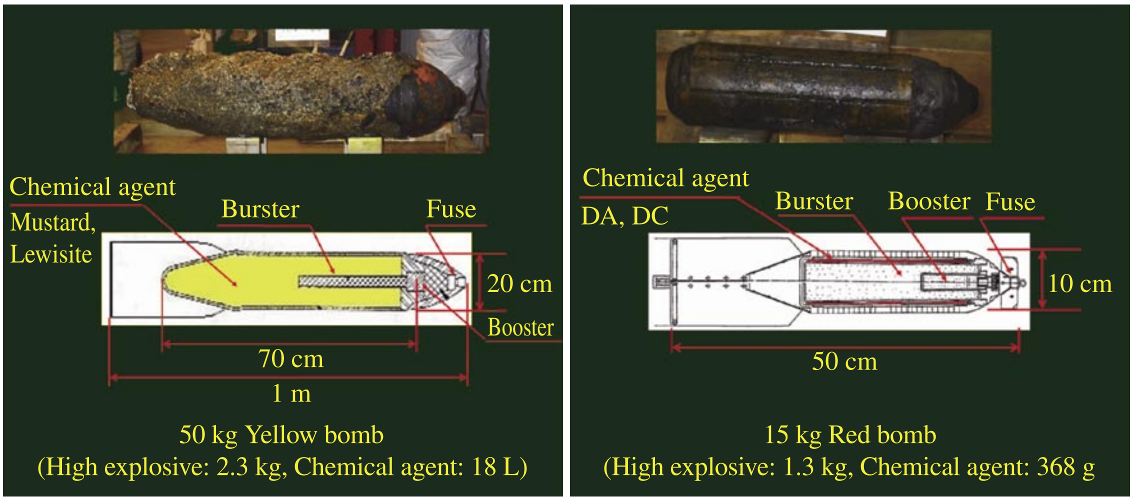


Fig. 1 Chemical bombs.

Fig. 2 Buster tube of 50 kg yellow bomb.

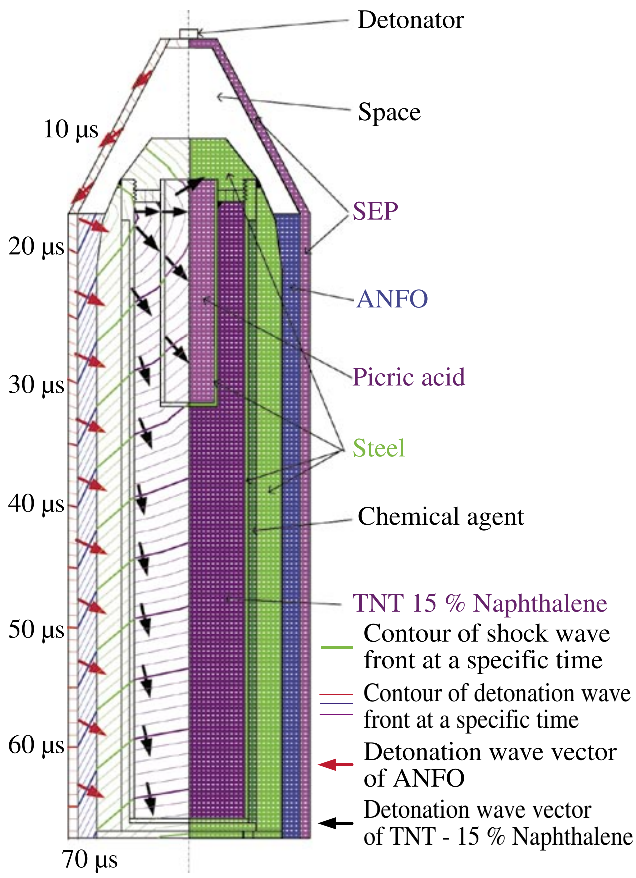


Fig. 3 Detonation propagation in implosion process of a simulating 15 kg Red bomb.

isentrope curve and the R-H curve for iron.

3) As the shock Hugoniot data of chemical agent is not known, shock wave velocity in chemical agent is assumed to be the same as steel, because the chemical agent is thin and enclosed by the steel shell.

The behavior of the shell is examined when the two groups of explosives detonate on both sides with time lag. To reduce the fragment speed, the following two phenomena are essential.

1) Increase the particle velocity behind the shock front in steel from outside to inside by controlling the detonation wave vectors of donor charge to be perpendicular to the steel shell.
2) Decrease the particle velocity in steel from inside to outside by controlling detonation waves of the burster and booster to turn as parallel as possible to the shell.

The detonation initiated by the detonator propagates through SEP and ANFO. The shock wave injected through the steel shell, the layer of chemical agent and the thin steel layer initiates the detonation of the burster (TNT-15 % Naphtharene) and then the booster (picric acid). The whole process takes place in 70 μs in Fig. 3.

As the detonation velocity of SEP is roughly 2 times as that of ANFO, the detonation wave vector becomes almost perpendicular to the steel shell. When the burster starts detonating at the top part of the shell, the detonation wave travels towards the center axis of the burster initially. Since the burster also has a higher detonation velocity than ANFO, the detonation wave vector gradually changes its direction to parallel to the shell wall as the wave propagates. Through the detonation propagation process, the fragment velocity of the shell is decreased. This is the expected effect of implosion.

3. Emulsion explosive as donor charge

To realize implosion, a series of tests was conducted under different conditions.

3.1 ANFO

As a first step, ANFO was tested as donor charge. Figure 4 shows the models. Around the weapon model is placed ANFO covered with SEP as Fig. 4 indicates. As analyzed in Fig. 3, ANFO seems to be good for implosion, because the detonation wave velocity of SEP is more than 2 times as fast as that of ANFO.

Table 1 shows the characteristics of ANFO [3] used at the test.

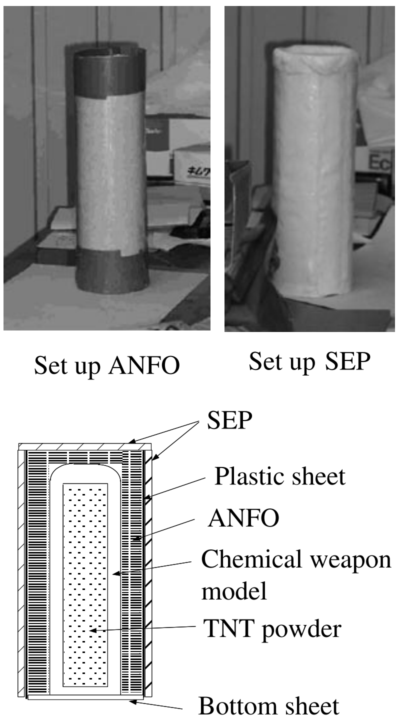


Fig. 4 Detonation test with ANFO.

Table 1 Characteristics of explosives in detonation test.

	Density (kg m^{-3})	Detonation velocity (m s^{-1})
ANFO (powder)[3]	850	about 3,000
Sheet explosive (SEP)[2]	1,280	6,000 - 6,300
TNT (powder)[5]	730	4,200

3.2 Slurry explosive

Slurry explosives are widely available as industrial explosive and the ones with fluidity can be easily set around munitions with maximum contact of the donor charge with the munitions. Thus, the authors tested a Japanese product, the main characteristics of which are listed at Table 2.

This explosive is effective and was used at Kanda Port project as many as 250 shots.

However, in winter, an imperfect detonation was observed due to the less sensitivity of the slurry explosive in lower temperatures. To avoid this problem, the explosive was warmed up in a hot bath up to 30 C before setting. Although this is useful as a temporary countermeasure, a fundamental improvement is required in order to utilize DA VINCH even in severe winter in the North East of China.

3.3 Emulsion explosive

The emulsion explosive made in Belgium is used as an alternative method. It is thought to be beneficial to solve the sensitivity problem that the slurry explosive has.

The emulsion explosive is produced by mixing a premix and solution, whereby the premix or the solution itself is not regarded as explosives. It facilitates the importation of the premix as it can avoid troublesome procedures including transportation approvals.

The main characteristic in its composition is inclusion of glass micro balloons as bubble maintaining agent.

Table 3 shows the result of detonation propagation test at the low temperature of -20 °C, which proves good performances: the detonation velocities are 5020 and 5176 m s^{-1} at -20 °C under proper a mixture of premix and solution.

Emulsion explosive has another advantage to control its composition easily.

To keep a fireball longer and to realize better Destruction and Removal Efficiency (DRE), an adequate amount of

Table 2 Characteristics of slurry explosive.

	Density (kg m^{-3})	Detonation velocity (m s^{-1})
Slurry explosive	1,150	5,600

Table 3 Detonation propagation test result of emulsion explosive.

Temperature (°C)	No.	Confinement	Detonation velocity (m s^{-1})
-20	1	Steel tube 42 mm	5,020
		PVC tube 46 mm	4,798
	2	Steel tube 42 mm	4,798
		PVC tube 46 mm	4,579
	3	Steel tube 42 mm	5,176
		PVC tube 46 mm	4,960

(a): Munitions are stored in a case.

(b): Pre-packed donor charge is used as it is, without unpacking.

(c): A chemical munition is encased in an emulsion type charge and hung in the inner chamber.

Fig. 5 Preparation of munitions.

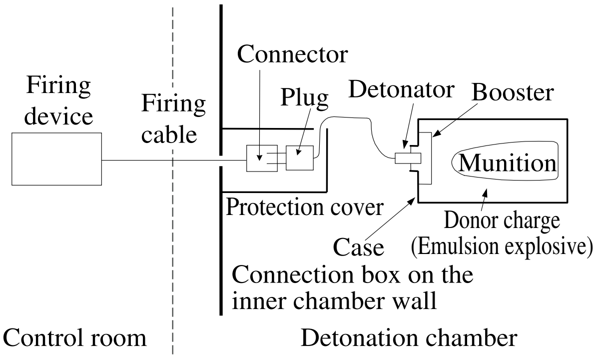


Fig. 6 Detonation chain.

Aluminum is added, considering the trade-off of viscosity and detonation velocity.

At Kanda, pre-packed emulsion is used without opening the pack, to avoid the charging operation of emulsion by pumping.

4. Detonation chain

The chemical munitions to be destroyed are surrounded by donor charge and hung in the inner chamber where the detonation is set off in a vacuum. The munitions are hung by a robotic arm. Figure 5 shows an example of state of the munitions in the chamber.

Detonation chain is designed to detonate a whole munition completely and no explosive is detected in the buster part of the munition.

Figure 6 shows a detonation chain used for DA VINCH. A sheet explosive (SEP) is used as a booster of emulsion explosive.

With regard to detonator, Electronic Delay Detonator (EDD) [6] is used for the sequential multi detonations, and Electric Detonator (ED) is used for simultaneous multi detonation. Exploding Bridge Wires (EBW) detonator was also tested as an alternative to ED, but was not good in vacuum condition. The higher voltage of EBW detonator causes short-circuiting under vacuum condition. The EBW detonator works at far higher voltage than the ED and is regarded safer than ED under influences of noises by mobile phones, high electrical current or high voltage antennas because it needs higher energy to ignite.

At Kanda, there was no such influence of noises from outside. Mobile phones are strictly prohibited within the detonation area. In these circumstances, ED is safe enough as EBW.

5. Sequential multi detonations and simultaneous multi detonations

To detonate a certain amount of explosives separately in one shot remarkably reduces the damage to the chamber when compared to the single detonation which detonates all the explosives in one bunch.

5.1 Sequential multi detonations

Depending upon the size of the munitions, several chemical munitions can be detonated in the inner chamber sequentially with appropriate distance. Electronic-Delay Detonators containing self-timers control the timing of the sequential multi detonations. The use of sequential multi detonations significantly reduces the impulsive pressure, which eventually decrease the fatigue damage to DAVINCH, as shown in Fig. 7.

The red marks in Fig. 7 show two sequential multi detonations in the same shot, whereas the blue ones display single detonations. For instance, two 15 kg TNT, sequential multi detonations of total 30 kg TNT is plotted at 15 kg TNT in ■ , and a single detonation of 15 kg TNT is plotted at 15 kg TNT in ◆ .
The damages caused at 30 kg of TNTeq for sequential multi detonations are similar to a 15 kg single detonation, which means that multiple detonations are safer and give less damage to the chamber than single detonations.

In Kanda, more than 260 shots were successfully carried out by the sequential multi detonations to destroy 600 munitions.

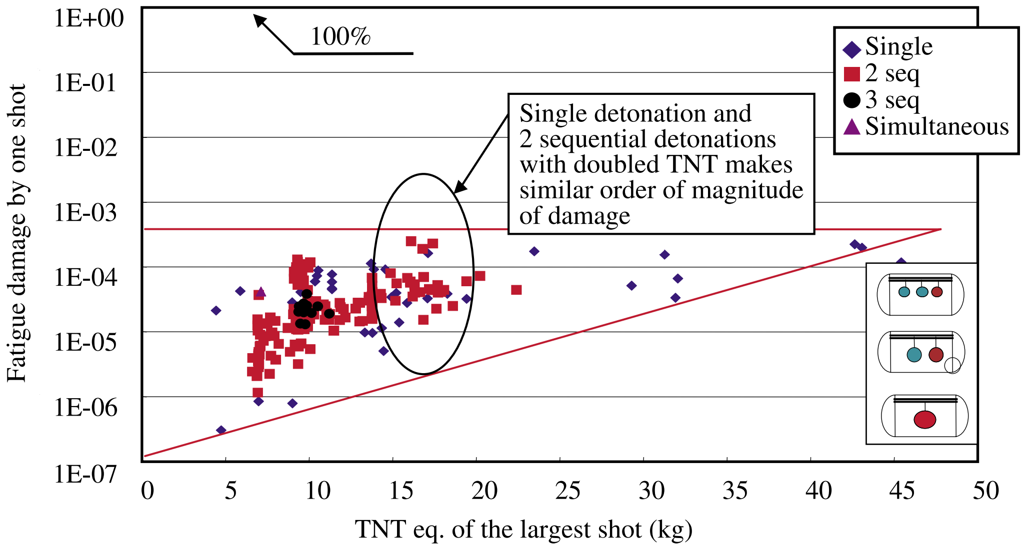
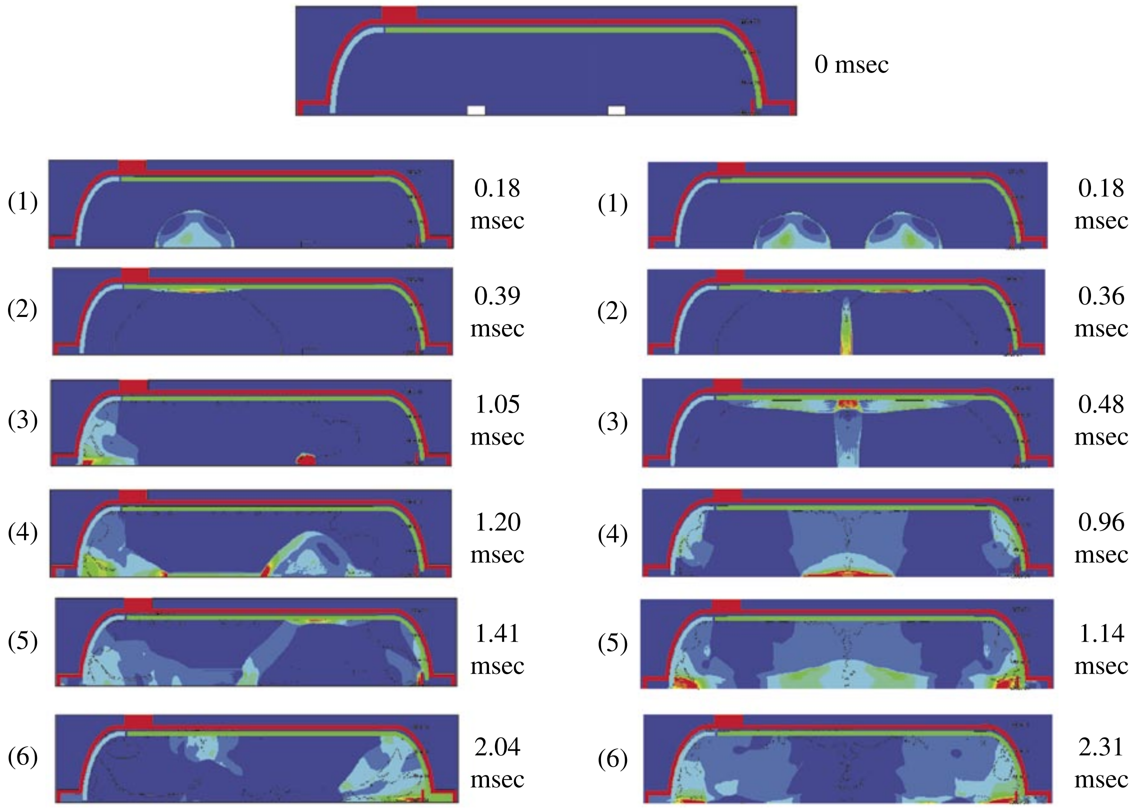


Fig. 7 Sequential multi detonation damages compared to single detonation.



(a) Sequential multi detonation (b) Simultaneous multi detonation

Fig. 8 Dynamic analysis of two detonation modes.

5.2 Simultaneous multi detonations

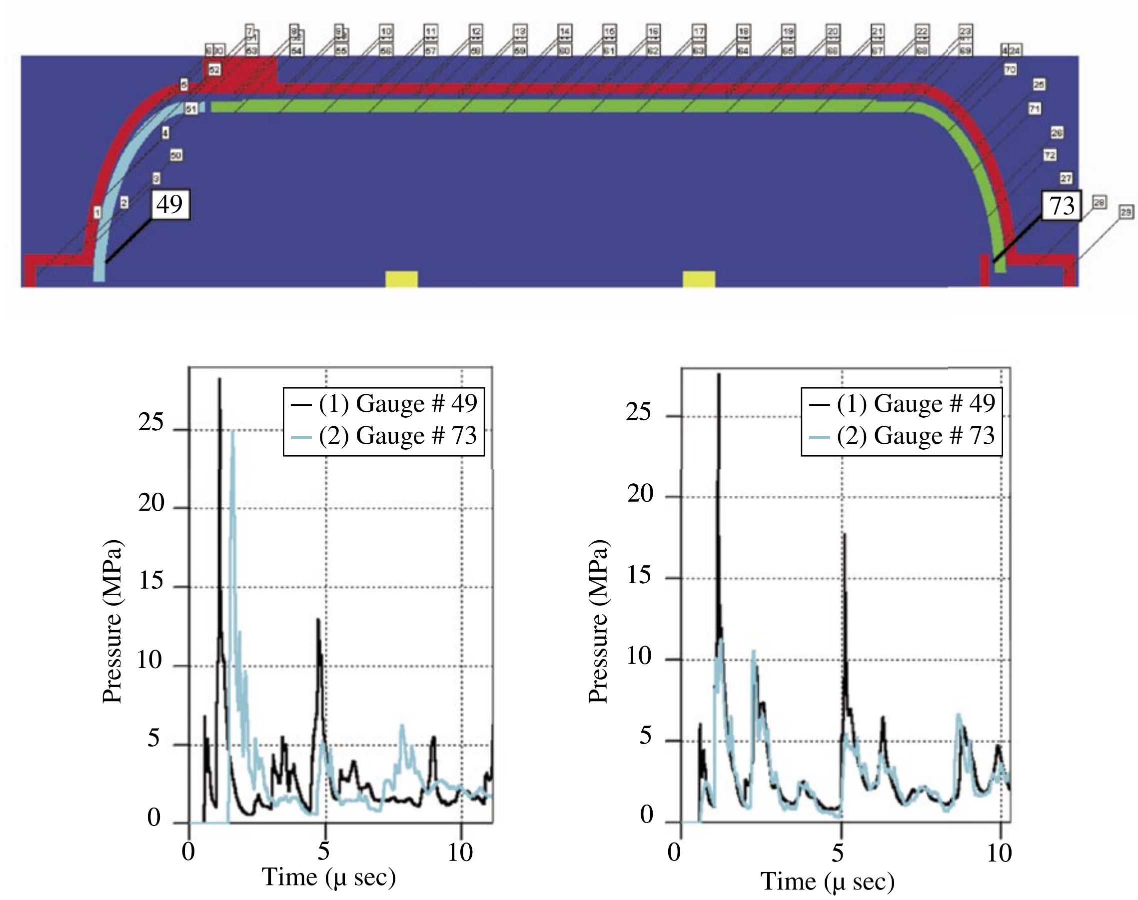
The other method to decrease the damage to the chamber is simultaneous multi detonations which detonate several packages of munitions in an adequate distance concurrently and not in progression.

The difference between the sequential multi detonations and simultaneous multi detonations are concerned with the behavior of the detonation shock wave; the former is asymmetric whilst the latter symmetric.

5.3 Comparison of two multi detonations

Figure 8 shows the results of the analysis by AUTODYN. The analysis is based on two 15 Kg TNT targets installed in the chamber. The sequential multi detonations (a) of Fig. 8 are the detonation of two charges with the interval of 1 ms, while the simultaneous multi detonations (b) of Fig. 8 are the detonation of two charges at once without delay.

In the sequential multi detonations, the 1st shock wave



a) Sequential multi detonation b) Simultaneous multi detonation

Fig. 9 Pressure-time histories of two detonation modes.

reaches the cylindrical wall of the inner chamber 0.39 ms after the 1st detonation of the chamber ((a)-(2) in Fig. 8) and then reflects on the wall. Before the 2nd shock wave reaches the wall of the inner chamber, the 1st shock wave has disappeared on the wall ((a)-(5) in Fig. 8). At the center of the left head, the impulsive load becomes maximum 1.05 ms after the 1st detonation ((a)-(3) in Fig. 8). In the meantime, at the center of the right head, the impulsive load becomes maximum after 1.41 ms. At 2.04 ms, 2nd impulsive load reaches the maximum at the center of the right head, due to the superposition of shock waves reflected on the entire surface of the wall.

In the simultaneous multi detonations, the shock waves of two 15 Kg TNT detonations reach two different points on the cylindrical wall after 0.36 ms respectively ((b)-(2)) and the maximum impulsive load appears at the middle of the cylindrical wall by the interaction and superposition of two shock waves after 0.48 ms((b)-(3)). After 1.14 ms, the two heads (left and right) have the highest impulsive loads by the shock waves reflected from the inner chamber wall ((b)-(6)).

In the simultaneous multi detonation, a proper distance between the packages of munitions can change the superposition mode of the shock wave, which reduces the damage to the chamber.

None of the "Non-Stockpile" munitions to be destroyed is the same in terms of condition, thus the symmetry of the simultaneous multi detonation is not achievable in practice.

Figure 9 shows the pressure-time histories of two detonation methods at two important points of 49 and 73. The first detonation shock wave is dominant comparing to the subsequent reflection waves. The first shock wave pressures of two detonation methods are around 27 MPa and have no large difference.

The damages caused by a certain TNT eq vary in a wide range, because of the effect of many other factors which are not taken into account in the dynamic analysis. Therefore, the monitoring of damages in the actual operation is necessary to evaluate the difference between the simultaneous multi detonation and the sequential multi detonation. As the damage of simultaneous multi detonation at 10 kg ● in Fig. 7 is within the range of damages caused by the two sequential detonations at the same TNTeq ■ ,simultaneous multi detonations are used now at Kanda to see the results of the two different detonation methods. The fatigue damage caused by the simultaneous multi detonation is expected to be the same order of magnitude as those of sequential multi detonations when the detonation conditions are properly controlled. The effect will be confirmed through the real operations at Kanda.

One of the advantages of the simultaneous multi detonation is the reduction of the detonator cost by using Electric Detonators (ED) instead of Electronic Delay Detonators (EDD).

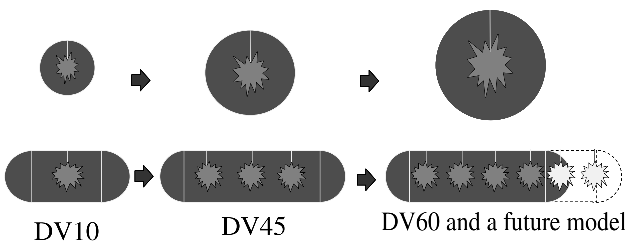


Fig. 10 Types of detonation.

6. Higher throughput

Through the experience of real records at Kanda Port, it is recognized that sequential multi detonation technology is useful to reduce the damage to the chamber and eventually can achieve the higher throughput by making the chamber longer.

Figure 10 illustrates the images of two types of detonation chambers.

Through more than a thousand of destruction of chemical weapons, cylindrical detonation chamber is proven to be effective to meet the increasing need of higher throughput of the future.

7. Conclusions

To establish a safer and more effective system of detonation of chemical weapons, a series of study was carried out on selection of emulsion explosives, on the detonation chains with EDD or ED, and on the effects of sequential and simultaneous multi detonations through actual operation.

Destruction of "Non-Stockpile munitions" is completely different from "Stockpile" or other experimental targets of high explosives because the nature and characteristics are usually unknown and/or beyond expectations. Therefore, a flexibility of system is required.

DA VINCH system is designed to have enough strength and good operation management system as described in the 1st paper: double walled structure; multilayered outer chamber; easy inspection and maintenance and eventually has operational flexibility. DA VINCH is a proven technology to meet this requirement through the experience in destructing over a thousand of chemical weapons.

8. Acknowledgement

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化学兵器の制御爆破チャンバーシステム(第二報):インプロージョン及びシーケンシャル爆破

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第一報に続き化学兵器を制御爆破処理するための爆破条件の研究を実施した。
①弾の炸薬による弾殻片飛散エネルギーを最小とするための,エマルジョン爆薬をドナーチャージとしたインプローション爆破法
②弾入りの複数パッケージをチャンバ内に同時に設置し,順次爆破してチャンバへの衝撃を大幅に緩和するためのシーケンシャル爆破法
これらの効果は苅田における 1,000 発以上の実化学弾処理において確認された。

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