研究論文

Low vulnerability, high performance, and superior aging of plastic bonded explosives

Hitoshi Miyoshi*

The primary characteristics of PBXs (Plastic Bonded Explosives) are low vulnerability, high performance, and superior aging, compared to the conventional explosives, i.e. TNT, Comp B, Octol and so on.

Chugoku Kayaku, Chuka, has been engaged in the study of PBXs for 22 years. In 1980, Chuka licensed production technology for PBXN-4. We proceeded to press the PBXN-4 molding powder and processed it with a lathe. We discovered that the performance and safety of PBXs were excellent. In 1983, Chuka initiated a study of castable PBXs using PBXN-105 as a baseline. We also licensed the production of PBXN-3, PBXN-5 and PBXN-301. Assisting in our development and study efforts was the fact that Chuka had the extensive experience in the production and quality control of HMX, RDX, and HNS (Hexanitrostilbene), which were the primary ingredients in PBXs. The development of PBXs has progressed smoothly. In order to differentiate Chuka's developed PBXs from others, we devised a naming convention. Chuka's PBXs were referred to as PBXK-C1106, PBXK-P1205 or PBXK-E6201. K stands for the initial letter of Chuka's president, Mr. Kozu. C means castable, P pressable, and E extrudable, respectively. The first digit of four figures means the main explosive that is comprised in the PBX; 1 is HMX, 2 RDX, 3 CL-20 (Hexanitrohexaazaisowurtzitan), 5 NTO (3-nitro-1, 2, 4-triazol-5-one), 6 PETN. The second digit is the type of binder systems; 1 is energetic binder, 2 inert binder. The third and fourth digits are consecutive numbers relating to the order of development.

In this paper, we will present our three developmental results of 2 PBXs as well as a combined composition study. The first composition is a low vulnerability PBX that consists of NTO, HMX, and binder. Shock sensitivity test, fast cook-off test, and other various tests were conducted. The results were ascertained safety performance. The second PBX studied consists of CL-20 and binder. This PBX has a high performance for metal acceleration. Detonation velocity for this PBX is about 8700 m s^{-1}. Since this PBX has a high flowability, loading it in complex shaped charge warheads is very easy. The third presented result is an aging study of 6 types of PBXs. In terms of aging theory for PBXs, we have identified no prevailing mechanism. We think that the real age exploration is the best way for confirming the aging phenomena. Since 1995, we have been conducting a variety of evaluation tests for the aged PBXs. These tests included detonation velocity, underwater explosion, card gap sensitivity, friction sensitivity, drop hammer sensitivity, DTA (Differential Thermal Analysis), TG (Thermal-gravimetry), tensile parameters test, vacuum stability test and nondestructive testing. Most studied PBXs of good aging performance were confirmed.

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*Chugoku Kayaku Co. Ltd., Yoshii Plant, 2530 Iwasaki, Yoshii-machi Tano-gun, Gunma 370-2131, JAPAN
TEL: +81-(0)27-388-5235
FAX: +81-(0)27-388-2612
e-mail: miyoshi@chugokukayaku.co.jp

1. Introduction

A series of serious munition accidents have happened over recent decades. Examples are the destruction of 43 aircraft at Bien Hoa, Vietnam in 1965 (27 dead, 95 injured); the 4 separate USN carriers between 1966 and 1981 (220 dead, 708 injured); and another accident at Bien Hoa in 1972 which destroyed 70 helicopters and the entire munitions stockpile (41 injured).

More recent events are the Camp Doha accident during Desert Storm (58 injured, 84 tanks/vehicles destroyed), the Kursk submarine tragedy (118 dead); the explosion of a truck-load of explosives in Xinjiang (60 dead, 170 injured); the Enschede fireworks depot explosion (20 dead, 562 injured); and the Bharatpur ammunition depot fire (2 dead, 10 injured). The consistent factor in all of these events is that the conventional vulnerable explosives involved led to catastrophic and ghastly consequences.[1)2)]

To enhance survivability of logistical and tactical systems, to reduce risk of injury to personnel, and to be potentially more cost effective and efficient to transport, store and handle, concept of insensitive munitions (IM) came onstage. IM is defined that "munitions which reliably fulfill their performance, readiness and operational requirements on demand, but which minimize the probability of inadvertent initiation and severity of subsequent collateral damage to weapon platforms, logistic systems and personnel when subjected to unplanned stimuli".[3)]

To produce IM, there are many approaches that the engineers and researchers all over the world have been studying. We figure that the development and application of PBXs are the most promising technical solution for producing IM. Chuka has been engaged in the study of PBXs for 22 years, and has acquired the manufacturing ability of all type of PBXs, they are, pressable, castable and extrudable PBXs.

The plant for castable PBXs is shown in Fig 1. The left picture shows to be removing the mixing rods from the container at the end of the mixing process. The mixed PBX in the container is moved to the loading position as the right picture shows. The piston is set over the container and pushes down the PBX to the projectiles or the warheads under deaeration.

At the outset of this paper, we present a low vulnerability NTO based PBX, which consists of HMX, NTO, aluminum powder and polyurethane binder. The composition ratio of these ingredients is 35, 30, 22 and 13 weight percent, respectively. The physicality tests, performance tests, safety tests and aging tests were conducted by comparing the NTO based PBX and PBXK-C1203 as a reference PBX. Secondly, the CL-20 based PBX is presented, and named PBXK-C3101, PBXK-C3102 and PBXK-C3201. The content of CL-20 is 81, 82 and 86 weight percent, respectively. The first two have the energetic binder system and the last one has the inert binder system. The performance tests

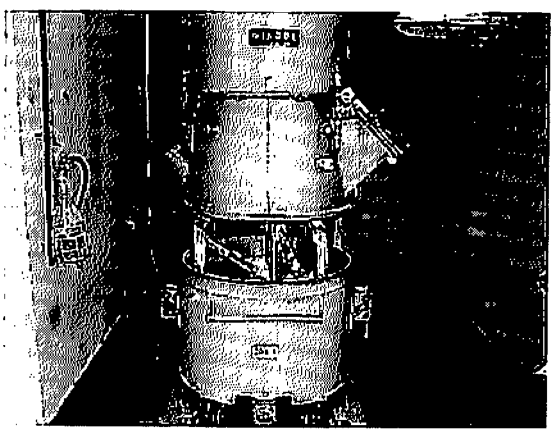
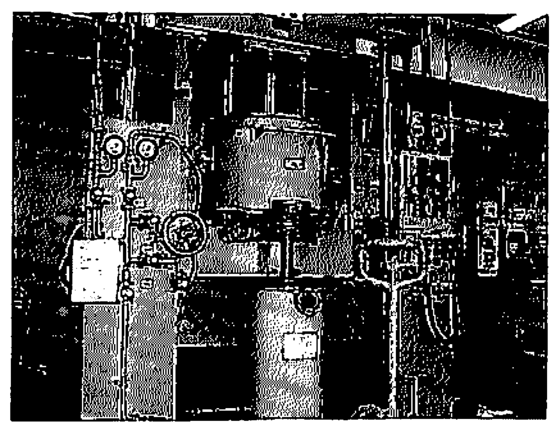

Fig. 1 The plant for castable PBXs.
The mixing process is shown in the left and the loading process right. In conformity with the Explosive Control Law, blast wave barriers surround the mixing facilities. The mixing process is conducted under deaeration and warming condition. After the mixing has been done, the container is moved to a loading position. The piston is set over the container and pushes down for removal of the mixed PBX under deaeration.

and safety tests was conducted. Lastly, we present an interim report of aging tests for six types of PBXs, they are, PBXK-C9102, PBXK-2203, PBXK-C2202, PBXK-C1203, PBXK-C1109 and PBXK-C1106. The ingredients and composition ratio of these PBXs will be presented in the section 4. These PBXs, manufactured in large volume, have been adopted for many types of munitions by the Japan Defense Agency.

2. Low vulnerability PBX

2.1 Experiments

The trend towards more deeply buried target of increased hardness imparts new requirements to be considered by the warhead designer. To meet the new requirements, high performance, low vulnerability PBXs are needed. NTO is a promising energetic material for such insensitive munitions[4][5]. Chuka has been studying NTO for about 10 years in order to determine its suitability for PBXs[6]. The main points of research of NTO are to control particle shape and distributions, as well as to develop an environmentally friendly synthesis.

The NTO based PBX was developed for a new missile warhead. This PBX consists of HMX, NTO, aluminum powder and polyurethane binder, and the composition ratio is 35, 30, 22 and 13 weight percent, respectively. PBXK-C1203 was selected as a reference explosive in order to evaluate performance of the NTO based PBX. PBXK-C1203 consists of HMX and polyurethane binder, and the composition ratio is 87 and 13 weight percent, respectively.

We conducted many tests over a four-week period at the Yoshii plant test range. The tests included as follows,

·Tensile strength, elongation and elastic modulus; compressive strength; coefficient of linear expansion; density. These tests were designed to concentrate on the physical properties of the PBX.

·Detonation velocity; peak overpressure and impulse. These tests were conducted for explosively performance.

·Ignition point; DTA; drop hammer sensitivity; friction sensitivity; electrostatic sensitivity; card gap sensitivity; Susan test; bullet impact sensitivity; fast cook-off test. These tests were evaluated for safety performance.

·Vacuum stability; tensile strength, elongation and elastic modulus; compressive strength; coefficient of linear expansion; density; detonation velocity; peak overpressure and impulse; DTA. These tests were controlled for aging performance.

2.2 Results and discussions

The results of these tests are shown in Table 1. The results were similar for most parts. We would like to discuss the results associated with a low vulnerability or insensitivity.

The Susan test was designed to measure the effectiveness of penetrating hard targets by the projectile loaded explosives. The results of the test, therefore, are very crucial to design the insensitive munitions. There are many evaluation methods of the Susan test, but we selected the method of comparing projectile velocities at a 20 % of relative energy release. The result for PBXK-C1203 was 397 m s^{-1} and for the NTO based PBX 421 m s^{-1}. The NTO based PBX demonstrates excellent insensitive performance 6 % higher against hard targets than PBXK-C1203. For the sake of comparison, the Susan test results of Comp B are added Fig. 2. As you can see, Comp B indicates 55% higher level of the energy release than the NTO based PBX and PBXN-C1203 at the impact velocity of 400 m s^{-1}.

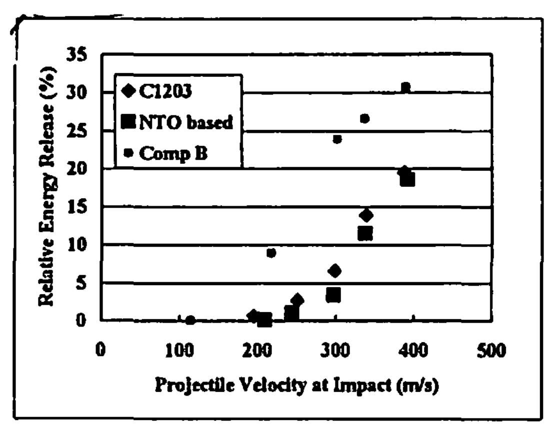

Fig. 2 The Susan test results.
Comparing with 20 % of relative energy release, the NTO based PBX is superior insensitive performance than PBXK-C1203. But, you can recognize at a glance that these PBXs have the property of excellent insensitivity to Comp B.

Table 1 Tests results for PBXK-C1203 and NTO based PBX

Test Items		Units	Temp. (C)	PBXK-C1203 A*	PBXK-C1203 B*	NTO based PBX A*	NTO based PBX B*
Tensile strength, elongation and elastic modulus	Tensile Strength	kg cm^{-2}	-35	3.1	4.6	5.5	8.7
			20	2.0	2.2	1.8	3.8
			71	1.7	1.9	1.4	2.8
	Elongation	%	-35	5.7	3.9	10.0	6.0
			20	15.8	5.6	13.9	6.0
			71	17.5	7.1	16.1	7.8
	Elastic Modulus	kg cm^{-2}	-35	81.7	303.9	78.3	354.1
			20	22.7	110.7	24.4	108.2
			71	20.4	58.8	14.0	64.9
Compressive strength		kg cm^{-2}	-35	11.5	10.4	19.0	23.2
			20	4.3	6.0	8.6	11.8
			71	3.1	4.5	7.1	8.0
Coefficient of linear expansion		1 C^{-1}	-35	6.5e-5	7.5e-5	6.1e-5	7.0e-5
			71	7.5e-5	7.7e-5	6.4e-5	7.2e-5
Density		g cm^{-3}		1.69	–	1.769	1.770
Detonation velocity		m s^{-1}		8200	8300	7430	7320
Peak overpressure and impulse: P. O.		MPa		1.72	1.73	1.20	1.40
Peak overpressure and impulse: Impulse		Pa-s		2.39e2	3.34e2	2.68e2	2.95e2
Ignition point: 4 second delay		C		No fire	–	No fire	–
DTA: Exothermic start temp.		C		180-210	204	219	221
DTA: Exothermic peak temp.		C		250-280	252	248	247
Drop hammer sensitivity		1/6 explosion:cm		49	–	17.5	–
Friction sensitivity		kgf		19.2	–	>36	
Electrostatic sensitivity		J		>0.45	–	>0.45	
Card gap sensitivity		Gpa		1.91	1.71	2.24	2.04
Susan test	20% Relative energy release m s^{-1}			397	–	421	–
Bullet impact sensitivity		Reaction level		Burning	–	Burning	–
Fast cook-off test		Reaction level		**		***	
Vacuum stability		Gas volume mlg^{-1}		0.050	0.027	0.057	0.039

* A: Immediately after making samples B: Expose at 71C for 28 days
** No reaction & Burning *** No reaction

The card gap test is also important to evaluate the sensitivity of explosives against shock wave. The shock wave pressure required for a 50 % detonation probability is 1.92 GPa of PBXK-C1203 and 2.24 GPa of the NTO based PBX.

The fast cook-off tests were conducted by using simulated warheads with an external diameter of 80 mm. When two samples were tested, both were "No reaction" in case of the NTO based PBX, while the results of PBXK-C1203 were "No reaction" and one "Burning".

Based on these results, we confirmed that the NTO based PBX was more insensitive than PBXK-C1203.

3. CL-20 based PBXs

3.1 Experiments

CL-20 is a high-energy, high-density solid energetic material or explosive. CL-20 was first prepared in 1987 by Dr. Arnold Nielsen at NWC (now Naval Warfare Center Weapons Division, China Lake). Formulations based on CL-20 are being designed and evaluated for explosive, rocket, and gun propellant applications.[7)]

Chuka started an investigation of CL-20 in 1996, in order to use it in PBXs for shaped charge

Table 2 Tests results for CL-20 based PBXs and reference PBXs

Test Items	Units	PBXK-C3101	PBXK-C3201	PBXK-C1106	PBXK-C1203
Detonation velocity	m s^{-1}	8650	8400	8360	8200
Card gap sensitivity	mm	59	57	44	44
Vacuum stability	ml g^{-1}	*	0.40	0.02	0.04
DTA; Exothermic peak temp	C	197	198	250	250

* Incapable measurement

warheads that have high penetration performance. There are two approaches for prepared PBXs in case of loading shaped charge warheads, that is, press or cast. You can smoothly and easily fill warhead having complex inner structures with the castable PBXs, but it is difficult to produce a composition ratio that comprises more explosive filler. From technical papers we have studied worldwide application examples of the pressable PBXs[8)-10)], and Chuka has about 20 years of experience in manufacturing the PBXs. We figured that you could not precisely assure the adhesiveness between the pressed explosive fillers and the liner material of shaped charges. Therefore, Chuka has decided to select the castable PBXs for shaped charges that have high penetration performance.

Initially, numerous tests were run in order to evaluate the performance and safety of CL-20 based PBXs. That is to say, detonation velocity, card gap sensitivity, vacuum stability and DTA were carried out for two months.

PBXK-C3101 and PBXK-C3201 were tested with a CL-20 content of 81 and 86 weight percent, respectively. An energetic binder system, using BDNPA/F as an energetic plasticizer, was used for PBXK-C3101 and inert one PBXK-C3201. PBXK-C1106 and PBXK-C1203 were selected as the reference PBXs. PBXK-C1106 consists of HMX and energetic binder, with the composition ratio of 82 and 18 weight percent, respectively. The ingredients and ratio of PBXK-C1203 have already been mentioned.

3.2 Results and discussions

The results of these tests are shown in Table 2. In the table, PBXK-C1106 has been selected as an explosive for shaped charges because of the high detonation velocity. Compared to detonation velocity of PBXK-C1106, PBXK-C3101 is 3.5 % higher, 8650 m s^{-1}, and PBXK-C3201 is 0.5 % higher, 8400 m s^{-1}. The sensitivity against shock wave of PBXK-C3101 and PBXK-C3201 is lower than reference PBXs, but we figured that the low sensitivity was due to high binder ratio, although sensitivity of CL-20 was higher than one of HMX.

In order to obtain better penetration performance, the studies for increasing the content of CL-20 has been carried out. With optimizing particle distributions of CL-20, PBXK-C3102 was developed. PBXK-C3102 consists of CL-20 and energetic binder, and the composition ratio is 82 and 18 weight percent, respectively. PBXK-C1106 was selected as a reference PBX. The energetic binder ratio of PBXK-C-3102 and PBXK-C1106 is identical, and explosive filler of these PBXs is CL-20 and HMX, respectively.

The shaped charge warheads of specific charge diameter, incorporated copper liners, were tested, and the resulting penetration depths, penetration velocities, penetration profiles and jet velocities were noted. We partly present the penetration depths divided by the charge diameter (CD). The penetration data of PBXK-C-3102 were 7.6, 7.3 and 7.2 CD, and PBXK-C1106 7.1 and 6.8 CD. Performance of penetration of PBXK-C3102 was enhanced by about 6 %, compared to PBXK-C1106. Detonation velocity of PBXK-C3102 was measured at the same time with penetration tests, and the results were 8740, 8710 and 8670 m s^{-1}, and average 8710 m s^{-1}. Density of PBXK-C3102 was 1.84 g cm^{-3} as actual measurement, and achieved more than 99 % of the theoretical maximum density (TMD).

These tests were new ones. Chuka believes firmly that PBXK-C3102 is a promising PBX for the shaped charge warheads, although some production capabilities were required to improve.

4. Aging tests of six types PBXs

4.1 Experiments

Chuka has manufactured many types of PBX for a long time. So, it is important and essential to confirm the properties of aging, in order to ensure consistent quality and performance of PBX loaded munitions. The theoretical studies on aging of PBXs have been carried out by many scientists and engineers all over the world[11][12], but we believe that no reliable methods for confirming aging of PBXs exist so far.

Since 1995, Chuka has been conducting a variety of evaluation tests for aged PBXs. These tests included detonation velocity, underwater explosion, card gap sensitivity, friction sensitivity, drop hammer sensitivity, DTA, TG, tensile parameters test, vacuum stability test and nondestructive testing.

The composition ratio of PBXK-C1106 and PBXK-C1203 has already been mentioned, but other PBXs appear in this paper for the first time. PBXK-C9102 was primarily developed in 1984, improving sensitivity and productivity of PBXN-105. PBXK-C9102 consists of ammonium perchlorate, aluminum powder, RDX and energetic binder, and the composition ratio is 47, 22, 15 and 16 weight percent, respectively. This PBX has a unique characteristic that keeps blast pressure at a higher level than average explosives or PBXs. The ingredients of PBXK-C2202 and PBXK-C2203 are identical and the composition ratio differs. These PBXs consist of RDX and inert binder, and the compounding ratio of RDX is 85 and 80 weight percent, respectively. PBXK-C1109 consists of HMX, aluminum powder and energetic binder, and the composition ratio is 60.2, 23 and 16.8 weight percent, respectively.

4.2 Results and discussions

In order to confirm the aging of these PBXs, significant difference analysis and statistics analysis were implemented. The results were similar for most parts and we had no tendency to change properties of those PBXs due to aging. Therefore, we believe firmly that these PBXs have the property of superior aging, but from the results of card gap sensitivity, we found that sensitivity showed slightly

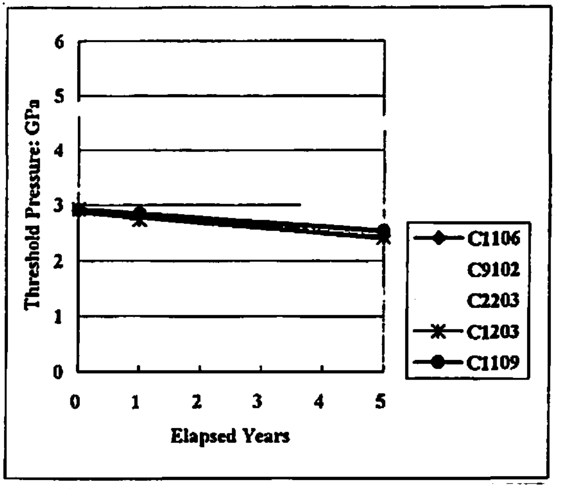

Fig. 3 Changing of sensitivity due to aging. Sensitivity increasing trends are found. But, the final conclusion of aging should be evaluated from the ten-year results.

an upward tendency due to aging. We consider that since these trends are the findings of five-year aging, the final conclusion of aging should be evaluated from the ten-year results. The results of card gap sensitivity were shown in Fig. 3. As you can see, the changing tendency of these PBXs is similar. Especially three types of PBX except for PBXK-C2203 and PBXK-C9102 are just all the same.

The ultimate goal of aging tests is to forecast damage and deterioration of PBXs in performance by accelerated aging tests. Samples are, for instance, applied 71C for 28 days. If the sample conditions of this accelerated aging test were equal to one of actual time, for instance, ten-year aging tests, it is said that the elapse of ten years is equivalent to expose samples at 71C for 28 days. In other words, you could predict the sample conditions after 10 years for 4 weeks.

In this paper, we cannot exhibit the interim data because analyses of aging are insufficient, and we don't want to present an imprecise conclusion. In five years' time we would like to present that data and propose an equation of conversion between accelerated times and actual years.

5. Conclusions

We confirmed through numerous tests that the NTO based PBX had the property of low vulnerability, and PBXK-C3102 also had high penetration performance. Aging tests were in progress, and reliable results will be obtained within five years' time. We would like to continue our research and development of PBXs for aiming at safer and higher performance.

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