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Simple Techniques for Predicting Sympathetic Detonation and Fast and Slow Cookoff Reactions of Munitions

by

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FOREWORD

This report describes simple techniques, which have been developed over many years, that can be used as tools to predict a munition's reaction to several stimuli. An explosive's response to shock-to-detonation transition (sympathetic detonation) can be predicted from large-scale gap test data. The techniques for predicting fast or slow cookoff time and severity of a reaction use laboratory data on the explosive, transient heat flow equations, and small-scale cookoff bomb test results for the reaction.

The study has been performed by the Naval Weapons Center (NWC), China Lake, Calif., over more than a decade, with data inputs from many programs. The work was supported by the Naval Air Systems Command under AIRTASK A540-540A/008-0/7000000001.

This report has been reviewed for technical accuracy by Toshio Inouye.

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(U) This report describes simple techniques, which have been developed over many years, that can be used as predictive tools. A simple data plot of given munition diameter versus large-scale gap test data on a given explosive is used to predict its response to shock-to-detonation transition. The techniques for predicting fast or slow cookoff time and severity of a reaction use laboratory data on the explosive, transient heat flow equations, and small-scale cookoff bomb (SCB) test results for the reaction.

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INTRODUCTION

The purpose of this report is to describe selected methods and techniques used to predict three major items: (1) sympathetic detonation of two similar munition rounds at zero or near zero separation distance, (2) time to cookoff for a munition round under fast or slow cookoff test condition, and (3) the severity of the cookoff reaction. These methods and techniques are described in greater detail later in this report.

The operation in predicting a given event and examples of its use are given in this report. The discussion encourages use of these tools to screen existing and candidate explosives for application to a specific munition. The method could also be used to determine or evaluate the shock and thermal behavior of a given munition in regard to safety aspects of its use and storage.

PREDICTIVE METHODS AND TECHNIQUES

PREDICTING SYMPATHETIC DETONATION

Sympathetic detonation involves the explosion or detonation of an explosive (acceptor) induced by the detonation of another explosive device (donor). The donor may be identical to the acceptor or it may be a different device altogether. Because munitions of the same type are usually stored together, it is typical to test identical donors and acceptors, although it might be possible to learn more about the sensitivity of cased explosives if a standard donor were used in all sympathetic detonation testing. In this report, the acceptor reaction is limited to a detonation, and the spacing between the donor and the acceptor is zero or near zero. Only one each of like donor and acceptor munition rounds is considered, and the donor fill is considered to have an explosive output similar to H-6 or Composition B explosive.

The development of an empirical method for predicting sympathetic detonation in a test is based on the calculated shock pressure at the interface between the high explosive and the munition case wall of the acceptor as developed by the donor munition. The induced shock pressure in the acceptor munition at zero or near zero separation distance was found for four different munition types. The calculated values for the 105 mm projectile were obtained from Reference 1; the calculated values for the Mk 81 and Mk 82 general purpose (GP) bombs are from Reference 2. Data on the Mk 40 warhead are from Reference 3. The information is listed in Table 1 with their calculated data and plotted in Figure 1 as inside diameter (inches) versus induced shock overpressure (kbars) in the acceptor.

The threshold for detonation of the explosive in the acceptor munition can be estimated from the large-scale gap test (LSGT) data (Reference 4); the data used are listed in Table 2. Gap pressure data from other sources, which use a larger acceptor charge diameter, are also included. These are the expanded large-scale gap test (ELSGT) (Reference 5) and 8-inch diameter heavily confined gap test (8-inch LSGT) (Reference 6). These larger scale gap tests were developed for measuring more shock-insensitive explosives.

Experimental data from sympathetic detonation tests from sources given in Reference 7 and related sources are listed in Table 3. The shock data given on each explosive are plotted in Figure 1. The calculated line in Figure 1 is the predicted separation between a go and a no-go in a sympathetic detonation test. The experimental data indicate that the predicted separation line is reasonably accurate. Exceptions will occur when the explosive output is well below the output of the H-6 or Composition B, such as the TNT/aluminum/wax mixture in Table 3. Then the apparent initiation pressure will also drop in value, as noted in Figure 1.

Using gap pressure data for a specific explosive can give a rough idea of what maximum munition size can be used and not initiate in a sympathetic detonation test. The plot in Figure 1 can be used in a limited manner on a new explosive. The graph is meant to be only a guide in the development or application of an explosive.

PREDICTING FAST COOKOFF TIME

A method used to predict the time to cookoff in a fuel fire for a munition is briefly described below.

Heat from the fuel fire is transferred to the warhead by free convection and radiation, and transferred within the munition by radial conduction into the liner material and the explosive. According to Reference 8, a simple equation for heat transfer through a unit area has, on integration, yielded Equation 1. Use Equation 1 to determine the cookoff time of an explosive-filled munition in a fuel fire.

$$\ell n(T_f - T)/(T_f - T_i) = \beta t \qquad (1)$$

where

T_f = flame temperature, K
T = temperature, K, at time, t, seconds
T_i = ambient temperature at time of test, K
β = equation constant determined from laboratory data

β values as determined from laboratory data are listed below for selected case thicknesses of steel. These values have been verified for a fuel fire condition. Other values of β can be determined from Equation 1 or from a log β versus log steel thickness plot.

Case thickness, inch	β, 1/second
0.500	0.0018
0.250	0.0037
0.125	0.0070
0.063	0.014

Once the β value versus steel thickness of the munition has been calculated, determine or select the flame temperature of the fuel fire. A typical value would be about 1300°F. Next, using Equation 1, determine the heating rate from 500 to 600 K at the inside surface of the munition case. This is an approximate temperature range where some explosives (e.g., RDX), have a maximum exothermic peak in this heating range. Once the heating rate has been determined, the actual exothermic peak temperatue for a given explosive can be determined from laboratory data (e.g., differential scanning calorimetry (DSC) thermal patterns for the specific explosive in question). Normally, the DSC patterns are determined at a series of selected constant heating rates. An example of this type of data is given in Table 4 on PBXN-106 explosive. The data presentation consists of a plot of log heating rate/T_m^2 versus $1/T_m$, as described in Equation 2.

$$\ell n(\text{heating rate})(E)/(T_m^2 R) = \ell n\, A(E/RT_m) \tag{2}$$

where

heating rate = K/s
T_m = exothermic peak absolute temperature, K
A = frequency factor, 1/s
E = activation energy, kcal/mol
R = 1.987 cal/mol·K

From this plot the activation energy, E, and frequency factor, A, can be calculated. An example of such a plot is given in Figure 2 from the DSC data in Table 4. The value of T, corresponding to the heating rate as determined above, is used to determine the time, t, from Equation 1. This is the predicted time to cookoff in a fuel fire for a bare case without internal liner material or external coating material. This time to cookoff does not include the time for the fuel fire to reach a "constant" temperature. There is usually a warm-up time of about 15 seconds for the fire to reach 800 K. Since almost all munitions have an internal liner of some type, Equation 3 describes the time-temperature relationship:

$$\ell n\, t' = \ell n\, t + CN \tag{3}$$

where

t' = time, in seconds, at liner/explosive interface
t = time, seconds, from Equation 1
C = constant for liner material, 1/mil
N = thickness of liner material, mil

The value of t' is the predicted time to cookoff for a given munition using an internal liner material. This is an empirical equation and does not consider chemical or phase changes that may occur in the liner material.

PREDICTING SLOW COOKOFF TIME

A method has been developed to predict the time to cookoff for a munition undergoing the slow cookoff test. The slow cookoff test has three steps in its operation. These are (1) the initial warm-up time to the soak temperature, (2) the time at soak temperature, and (3) the time to cookoff at a 3.3 K/hour heating rate. The temperature at cookoff can be estimated on the explosive used in the munition after the explosive has been evaluated using Equation 2 and a plot of the DSC data of the explosive in question has been obtained. These terms are seen in Equation 4:

$$t'' = t' + t^{\wedge} + t^{*} \tag{4}$$

where

t'' = total time, hours
t' = warm-up time, hours
$t^{\wedge}$ = soak time, hours, at a preselected temperature
t^{*} = time to cookoff at 3.3 K/hour

The predicted time to cookoff can be estimated using Equation 4. In an air-type oven, the warm-up time, t', takes about an hour to reach the soak temperature, but may require days for a large munition. The soak temperature is usually 60 K below the predicted cookoff temperature. The time held at this preselected soak temperature is based on the size and mass of the munition. For example, a munition weighing a couple hundred pounds could be soaked about 8 hours. This does not mean that the entire munition is at soak temperature, but that the munition case is at or near the soak temperature. After the soak period is over, the oven temperature is raised at a ramp rate of 3.3 K/hour until cookoff occurs.

PREDICTING SEVERITY OF COOKOFF REACTIONS

This section encourages the use of a small-scale cookoff bomb (SCB) as a tool to assess the severity of the cookoff reaction by examining the SCB case and witness plate damage caused by the explosive when subjected to external heat. Criteria are provided in Reference 9 for rating each test result as a burn, deflagration, explosion, or detonation based on the degree of damage sustained by the test fixture.*

The SCB experimental arrangement, materials, and procedures are given in Reference 9. The series of heating rates used in this study on severity of a cookoff reaction were approximately 2 K/second (similar to a bare munition case in a fuel fire), 0.2 K/second (similar to a thermally protected munition in a fuel fire), and 3.3 K/hour (the heating rate required for slow cookoff). The SCB tests can empirically demonstrate the cookoff reaction of the full-scale tests of munitions.

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* The SCB test fixture has been in use since 1968 with many hundreds of tests performed. For example, the SCB applications with other explosives and propellants in References 10 and 11 have shown good correlation to results from full-scale tests.

APPLICATION

An application of the methods and techniques described in this paper is made using PBXN-106 explosive. This is a nonaluminized RDX-based explosive intended for fragmentation munitions such as missile warheads and projectiles. This explosive has been tested in several projectiles and a 500-pound GP bomb.

The projectile of interest is the Mk 64, which has been studied in a series of sympathetic detonation tests. With a LSGT value of 30 kbars, the prediction line in Figure 1 would predict a non-reaction in the Mk 64 projectile. The experimental data gave a non-reaction for this series of testing.

The predicted fast cookoff time is determined in the following manner. The Mk 64 5"/54 projectile has a 0.65-inch-thick steel case wall with a 125-mil-thick internal liner material. The β value was determined for 0.65-inch-thick steel from a log-log plot of the β values versus steel thicknesses given above. The β value was 0.0014 1/mil. Using Equation 1, the heating rate was about 62 K/minute between 500 and 600 K, as shown below.

$t = [\ell n(1300 - 500)/(1300 - 300)]/0.0014 = 159$ seconds
$t = [\ell n(1300 - 600)/(1300 - 300)]/0.0014 = 255$ seconds
Heating rate = $(60)[(600 - 500)/(255 - 159)] = 62$ K/minute

At this heating rate, the peak reaction temperature is first estimated from the data in Table 4 at 50 K/minute. Using this estimate at 539 K and the plot in Figure 2, the estimated temperature is 544 K. On re-entering this temperature at this heating rate, the final predicted temperature is 543 K. At this temperature, a bare and unlined projectile would have a predicted fast cookoff time of 199 seconds (Equation 1).

$t = [\ell n(1300 - 543)/(1300 - 300)]/0.0014 = 199$ seconds

This projectile uses a 125-mil-thick liner material of polypropylene/polyethylene, which has a C value of 0.0017 1/mil. Using Equation 2,

$\ell n t' = \ell n(199) + (0.0017)(125)$
$t' = 246$ + warm-up time of 15 seconds
Predicted time = 261 seconds
Time measured = 262 seconds (average of four tests)
(Data range = 249-271 seconds)

This technique of predicting the time to cookoff for a munition in a fuel fire can be done by using Equations 1 and 2 and data such as that given in Figure 2. This prediction is based on laboratory data.

The slow cookoff predicted time depends on the time to reach soak temperature, the time held at the soak temperature, and the time to reach the cookoff temperature at 3.3 K/hour. In the slow cookoff test, the Mk 64 projectiles were conditioned at 366 K for 8 hours prior to commencing the controlled temperature. The predicted cookoff temperature is determined in a manner similar to a fast cookoff calculation. Divide the 3.3 K/hour by 3600 followed by the lowest temperature squared in Table 4 (461 × 461), which would yield a value of 4.3×10^{-9}/s·K. This would correspond to a temperature of 451 K. Using this temperature of 451 in the same manner, a final temperature of 452 K is obtained for a heating rate of 3.3 K/hour. The predicted time to cookoff would be:

Predicted time = (452 - 366)/3.3 = 26 hours
Total time = 26 + 8 = 34 hours

Since the data for cookoff time were not available, the predicted cookoff temperature was compared to the experimental value. The predicted temperature at cookoff for this heating rate of 3.3 K/hour was 452 K. The experimental value for the PBXN-106 explosive had an average value of 428 K for both Mk 165 and Mk 64 projectiles. A thermal stability problem has been detected during aging at elevated temperatures in related studies.

The cookoff reaction of PBXN-106 has been tested at NWC only once in a SCB under conditions similar to a fast cookoff test. The cookoff reaction was mild, but under heavier confinement, the cookoff reaction has been more severe. The fast cookoff test results were a burning reaction with both Mk 165 and Mk 64 projectiles. The most violent slow cookoff reaction of a projectile was an explosion (Reference 7).

The use of these predictive techniques with other explosives and propellants are given in References 10 and 11. The laboratory results were used to predict the temperature of cookoff and the time to cookoff of full-scale test items or munitions.

COMMENTS

The techniques and methods given in this paper can be used to evaluate a new or existing explosive in regard to sympathetic detonation with similar munitions as the donor and the acceptor. Figure 1 is only a crude estimate of the pressure at the acceptor case/explosive interface as developed by the donor. When the donor explosive has a lowered detonation pressure value, as in the case of the wax being added to TNT-based formulations, this will reduce the pressure at the acceptor case/explosive interface.

The application of these techniques and methods for predicting the time and temperature for fast and slow cookoff tests have been in use for many years with good results. They are simple and easy to use. They are a guide to estimate the cookoff time for a munition that may have changes in explosive fill or liner material.

The SCB and similar test fixtures have been in use for almost 20 years. The main use is in the development of new explosives and liner materials to help assess the severity of the cookoff reaction. The level of confinement can be changed to match more closely the munition being studied. The help here is in matching a given explosive formulation to a specific munition.

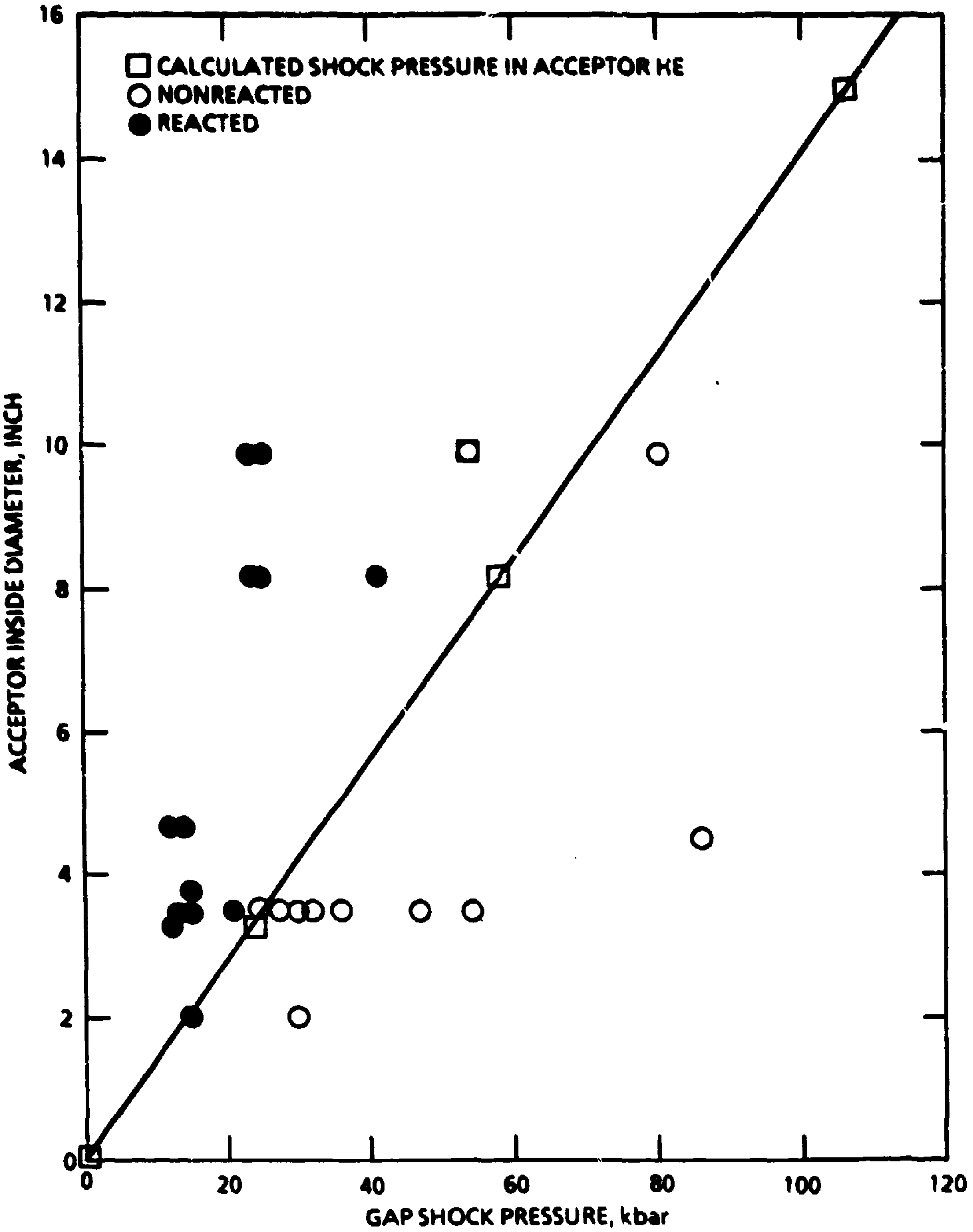

FIGURE 1. Plot of Acceptor ID vs. Initiated Shock Pressure Data.

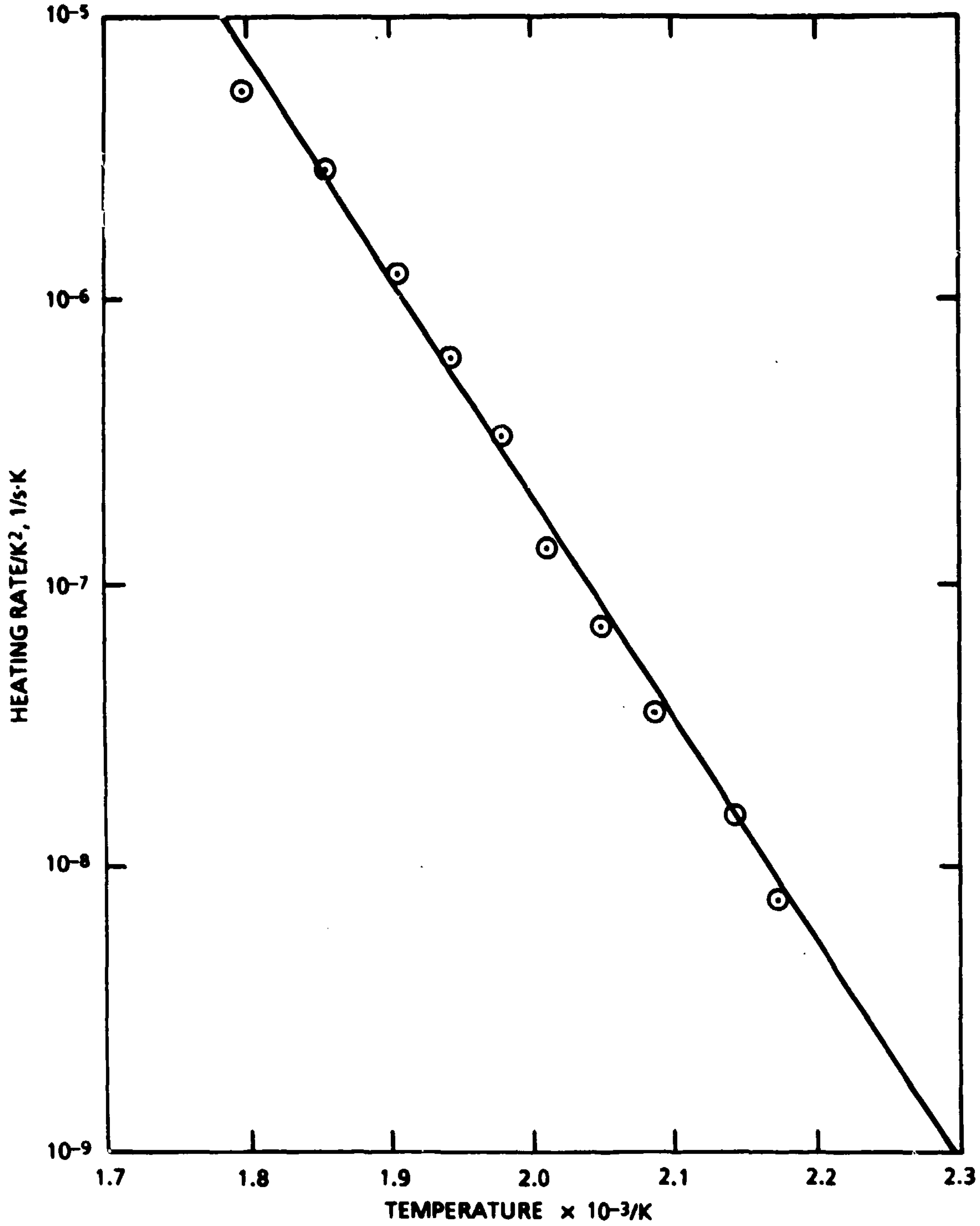

FIGURE 2. Plot of DSC Peak Data for PBXN-106 Explosive.

TABLE 1. Calculated Shock Pressure in Acceptor HE at Separation Distance Listed for Sympathetic Detonation Tests.

Test item	Size, in.[a]			Donor/acceptor explosive	Induced acceptor shock pressure, kbars	Reference
	OD	ID	SD			
M1, 105 mm	4.1	3.3	0.0	Composition B	24	1
			0.4		42	
			0.8		36	
			1.2	↓	38	
Mk 81 bomb	9.0	8.2	0.1	H-6	58	2
Mk 82 bomb	10.8	9.9	0.7		54	2
Mk 40 warhead	16.5	15.0	0.0		106[b]	2
			9.3		40.5	3
			11.7		28.0	3
			15.3	↓	17.2	3

[a] OD = outside diameter; ID = inside diameter, SD = separation distance from munition surface to munition surface.

[b] Estimated from data in Reference 3.

TABLE 2. Selected Initiation Shock Pressure Values for Several Explosives and Propellants.

High explosive or propellant	Density, g/cm³	Shock pressure, kbars[a]		
		LSGT	ELSGT	8-in. LSGT
TNT	1.62	44 (C)	~15 (C)	14 (C)
Tritonal	1.72	46 (C)		15 (C)
AFX-1100	1.59	...		50 (C)
Destex	1.61	51 (C)		
TNT/NQ	...	...		42 (C)
TNT/aluminum/wax	...	...		54 (C)
RDX	1.64	7 (P)		
Composition A-3	1.50	15 (I)		
Composition B	1.72	19 (C)		12 (C)
H-6	1.75	30 (C)		13 (C)[b]
RDX/NQ/PU	...			~80 (C)
Ammonium picrate	1.55	36 (H)		
PBXN-103	1.88	54 (C)		
PBXN-106	1.64	30 (C)		
PBXN-107	1.65	41 (C)		
PBXN-109	1.66	24 (C)		
PBXC-117	1.76	32 (C)		
PBXW-113	1.67	27 (C)		
PBXW-114	1.70	27 (C)		
PBXW-115	1.79	47 (C)		
PBX(AF)-108	1.56	21 (C)		
N-12	1.54	86 (P)		

[a] C = cast; P = pressed; H = hydraulically pressed; I = isostatically pressed.

[b] The estimated 13 kbar value was determined from the 8-inch LSGT data on TNT, Tritonal and Composition B.

TABLE 3. Sympathetic Detonation Test Data.

Munition type	OD	ID, in.	Donor/acceptor explosive	Acceptor detonation
Mk 165	76 mm	2.0	Composition A-3	Yes
	76 mm	2.0	PBXN-106	No
M1 projectile	105 mm	3.3	Composition B	Yes
HEP projectile	105 mm	3.8	Composition A-3	Yes
Mk 64	5"/54	3.5	Composition A-3	Yes
↓	↓	↓	Composition B	Yes
			H-6	Yes
			Explosive D	No
			PBXN-103	No
			PBXN-106	No
			PBXN-109	No
			PBXC-117	No
			PBXW-113	No
			PBXW-114	No[a]
			PBXW-115	No
			PBX(AF)-108	Yes
Steel cylinder	5 inch	4.5	N-12	No
↓	155mm	4.7	Composition B	Yes
	155mm	4.7	TNT	Yes
Mk 81 bomb	9.0 inch	8.2	Tritonal	Yes
↓	↓	8.2	H-6	Yes
		8.2	PBXN-107	Yes
Mk 82 bomb	10.8 inch	9.9	Tritonal	Yes
↓	↓	9.9	RDX/NQ/PU	No
		9.9	H-6	Yes
		9.9	TNT/aluminum/wax	No

[a] One test reacted at a standoff distance of 3 inches.

TABLE 4. DSC Data for Thermal Decomposition of PBXN-106 Explosive.

Heating rate, K/min	Peak temp., K	Temp., $1/K \times 10^3$	Heating rate/K^2 $\times 10^7$
0.1	461	2.170	0.0785
0.2	467	2.143	0.153
0.5	479	2.087	0.363
1.0	488	2.048	0.700
2.0	498	2.010	1.35
5.0	505	1.980	3.37
10.0	514	1.946	6.31
20.0	524	1.909	12.2
50.0	539	1.857	28.7
100.0	556	1.798	53.9

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ACRONYMS

DSC	differential scanning calorimetry
DTG	derivative thermogravimetry
ELSGT	expanded large-scale gap test
GP	general purpose
HE	high explosive
LSGT	large-scale gap test
NQ	nitroguanidine
PBX	plastic-bonded explosive
PU	polyurethane
RDX	cyclotrimethylenetrinitramine
SDT	shock-to-detonation transition
SCB	small-scale cookoff bomb
SSCB	super-small-scale cookoff bomb
TNT	trinitrotoluene

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  - Code 2031, P. Dendor (1)
  - Code 5246, Technical Library (1)
  - Code PM2C, J. Torres (1)
- 1 Naval Ordnance Station, Louisville
- 1 Naval Postgraduate School, Monterey (Library)
- 2 Naval Research Laboratory
  - Code 2627, W. Balwanz (1)
  - Technical Information Section (1)

- 2 Naval Ship Research and Development Center, Portsmouth
  - Library (1)
  - Underwater Explosions Research Division (1)
- 8 Naval Surface Warfare Center, Dahlgren
  - Code G-10 (1)
  - Code G-13, D. Dickinson (1)
  - Code G-22, T. Smith (1)
  - Code G-31 (1)
  - Code G-32, W. Isaacs (1)
  - Code H-10 (1)
  - Code R-15
    - D. Houchins (1)
  - Technical Library (1)
- 22 Naval Surface Warfare Center, White Oak Laboratory, Silver Spring
  - Code R-10 (1)
  - Code R-10B (2)
  - Code R-10C (1)
  - Code R-11 (1)
    - V. DeVost (1)
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    - L. Burke (1)
    - L. Montesi (1)
  - Code R-13 (1)
    - R. Bernecker (1)
    - J. Forbes (1)
  - Code R-14 (1)
  - Code R-15, M. Swisdak (1)
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    - E. Kayser (1)
    - A. Tompa (1)
  - Code R-17 (1)
  - Technical Library (1)
- 1 Naval War College, Newport
- 1 Naval Weapons Station, Concord (Code 321, M. Bucher)
- 4 Naval Weapons Station, Yorktown
  - Code 5021, L. Leonard (3)
  - NEDED (1)
- 3 Naval Weapons Support Center, Crane
  - Code 505, J. E. Short (1)
  - Code 506, A. Norris (1)
  - Code 90, A. E. Whitner (1)
- 1 Office of Naval Technology, Arlington (ONT-07)
- 2 Pacific Missile Test Center, Point Mugu
  - Code 2141, R. Taylor (1)
  - Technical Library (1)
- 1 Army Materiel Command, Alexandria (Technical Library)
- 1 Army Materiel Development and Readiness Command Field Safety Agency, Charlestown (Library)
- 1 Army Missile Command, Redstone Scientific Information Center, Redstone Arsenal (AMSMI-RD-CS-R/ILL Documents)
- 7 Army Ballistic Research Laboratory, Aberdeen Proving Ground
  - AMXBR-TBD, Dr. P. Howe (2)
  - DRDAR-BL, J. Frazier (1)
  - DRDAR-BLP, Watermeier (1)
  - DRDAR-BLT
    - R. Frye (1)
    - E. Pacanowsky (1)
  - DRDAR-TSB-S, STINFO (1)
- 1 Army Engineer Center, Fort Belvoir (Engineering School, Assistant Commandant)
- 2 Army Engineer School, Fort Belvoir
  - ATSE-CDC (1)
  - ATSE-DTE-ADM (1)
- 1 Army Engineer Waterways Experiment Station, Vicksburg (Library)
- 1 Army Research and Development Laboratory, Natick (Library)

- 1 Army Research Office, Research Triangle Park
  - Chemistry Division, G. Husk (1)
  - RDRD-IPL-CH, R. Ulsh (1)
- 1 Harry Diamond Laboratories, Adelphi (Technical Library)
- 1 White Sands Missile Range, (Technical Library)
- 1 Air Force Academy, Colorado Springs (FJSRL/NC, J. Wilkes)
- 6 Air Force Armament Laboratory, Eglin Air Force Base
  - AFATL/FX
    - COL M. Woodring (1)
    - M. Zimmer (1)
  - AFATL/FXE
    - T. Floyd (1)
    - G. Parsons (3)
- 1 Air Force Intelligence Service, Bolling Air Force Base (AFIA/INTAW, MAJ R. Esaw)
- 1 Air Force Office of Scientific Research, Bolling Air Force Base (T. Matusko)
- 1 Defense Advanced Research Projects Agency, Arlington (Library)
- 2 Defense Technical Information Center, Alexandria
- 4 Department of Defense Explosives Safety Board, Alexandria
  - DDESB-KT (1)
  - P. Price (1)
  - J. Ward (1)
  - T. Zaker (1)
- 1 Under Secretary of Defense for Research and Engineering (Technical Library)
- 1 Holston Defense Corportion, Kingsport, TN (Plant Manager)
- 8 Los Alamos National Laboratory, Los Alamos, NM
  - Mail Station 5000
    - M-1, Code 9101
      - H. Cady (1)
      - T. Larson (1)
    - M-3, MS960, W. Davis (1)
  - B. Dobratz (1)
  - H. Flaugh (1)
  - C. Mader (1)
  - R. Rabie (1)
  - L. Smith (1)
- 3 New Mexico Institute of Mining and Technology, Socorro, NM
  - T. B. Joyner (1)
  - M. L. Kempton (1)
  - J. P. McLain (1)
- 1 SRI International, Menlo Park, CA (D. Ross)
- 3 Sandia National Laboratories, Albuquerque, NM
  - Library (1)
  - J. Reed (1)
  - L. Vortman (1)
- 3 The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD
  - Code ML-P, Nichols (1)
  - J. Hannum (1)
  - L. Piper (1)
- 1 The Johns Hopkins University, Chemical Propulsion Information Agency, Laurel, MD
- 4 University of California, Lawrence Livermore National Laboratory, Livermore, CA
  - Code L-324, R. McGuire (1)
  - Code L-368
    - M. Finger (1)
    - E. Lee (1)
    - J. Kury (1)