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The Use of Combustible Metals in Explosive Incendiary Devices‡

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Abstract

We have investigated tailoring damage effects of explosive devices by the addition of unconventional materials, specifically combustible metals. Initial small-scale as well as full-scale testing has been performed. The explosives functioned to disperse and ignite these materials. Incendiary, enhanced-blast, and fragment-damage effects have been identified. These types of effects can be used to extend the damage done to hardened facilities. In other cases it is desirable to disable the target with minimal collateral damage. The use of unconventional materials allows the capability to tailor the damage and effects of explosive devices for these and other applications. Current work includes the testing of an incendiary warhead for a penetrator.

Background

There is interest in enhancing or selectively damaging specific targets. For example, hardened targets may suffer minimal overall damage when breached by a conventional penetrator. It would be advantageous to extend the damage beyond the room in which the penetrator detonated. On the other hand, sometimes strategically limited damage is desirable. For instance, it can be useful to disable a power grid in such a manner that necessary utilities can be restored relatively quickly to the populace. In some cases, a device is needed that can be quickly installed by military personnel to breach a barrier or wall and then spread secondary effects inside the targeted structure.

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Materials

Combustible metals were chosen as the baseline materials for an incendiary effect. Magnesium, aluminum, titanium, zirconium, and hafnium were considered. Magnesium, aluminum, titanium, and zirconium were tested. Titanium and zirconium are more dense than magnesium and aluminum (4.53 and 6.4 vs 1.74 and 2.7 g/cm^3), a desirable factor for some explosive devices, e.g., penetrators. We expected hafnium to perform well as an incendiary but ruled it out because of cost and availability. (Hafnium exists as about 2% of zirconium ore).

Experimental Configuration

The experimental configurations are shown in Figure 1.

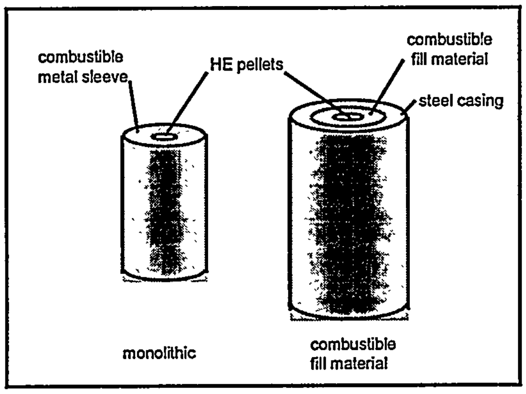

Figure 1. Monolithic and fill-material experimental configurations.

The length of the test unit was from three to twenty-four inches. The three-inch length simplified the assembly and testing, but was more susceptible to end effects. The OD (outer diameter) varied from 1.5 to 4.0 inches.

The monolithic configuration consisted of a thick-walled sleeve of a combustible metal with a column of high-explosive (HE) pellets in the center. The second configuration consisted of a cylindrical steel casing, an annulus of a fill material pressed in the cylinder, and a central column of HE pellets. The steel casing was made of 4340 heat-treated to a Rockwell hardness of 40 R_c or a 1018 carbon steel. The combustible fill materials that were tested in this configuration included:

- titanium sponge with an average particle size of 0.8 mm;
- zirconium gravel with an average particle size of 3 mm;
- zirconium sponge with an average particle size of 1 mm;
- zirconium washers 2 mm thick.

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The titanium sponge was used at bulk density, approximately 2.25 g/cm^3. The zirconium sponge and gravel were pressed to 12 ksi resulting in a range of 42% to 63% TMD (theoretical maximum density). Explosive pellets were inserted in the central core. Booster pellets and an exploding-bridgewire (EBW) detonator were installed on one end of the unit.

The test fixture was hung midway between the floor and ceiling of a steel test cell. Two test cells were used, one for the scaled-down tests (1 to 20) and another with a higher explosive rating for the full-scale penetrator warhead tests (21, 22, and 23). A top view of the test cell used for the scaled-down tests is shown in Figure 2. The arrangement in the test cell used in the full-scale penetrator tests is illustrated in Figure 3. Paper and newspaper were used in all tests except Test 23. Plywood and wood were used in Tests 14 through 22. In Tests 21 and 22, empty steel propane tanks were used to simulate canisters of chemical or biological agents. For these two tests, the front of the test cell was blocked by a stacked wall of 6000-pound concrete blocks backed by stacks of railroad ties and pallets of sand bags. For Test 23, this wall was removed to allow a clear view inside the test cell. A sheet of plywood and two empty propane tanks were used in this last test.

The detonation, dispersion of hot particles, and additional effects were monitored by 500-frame-per-second and standard video coverage as well as fast-framing cameras with internal and external views of the test cell. Flash X-ray was used in Tests 21 and 22 to measure the fragment velocity.

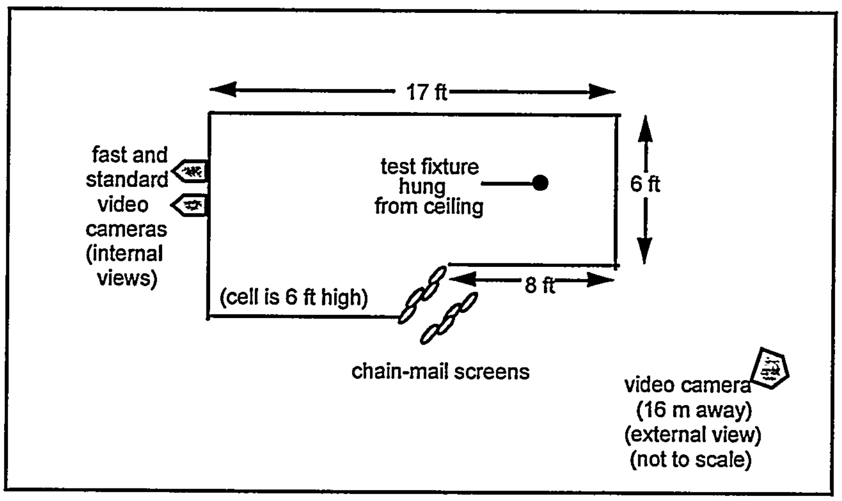

Figure 2. Top view of the test cell used for the scaled down tests.

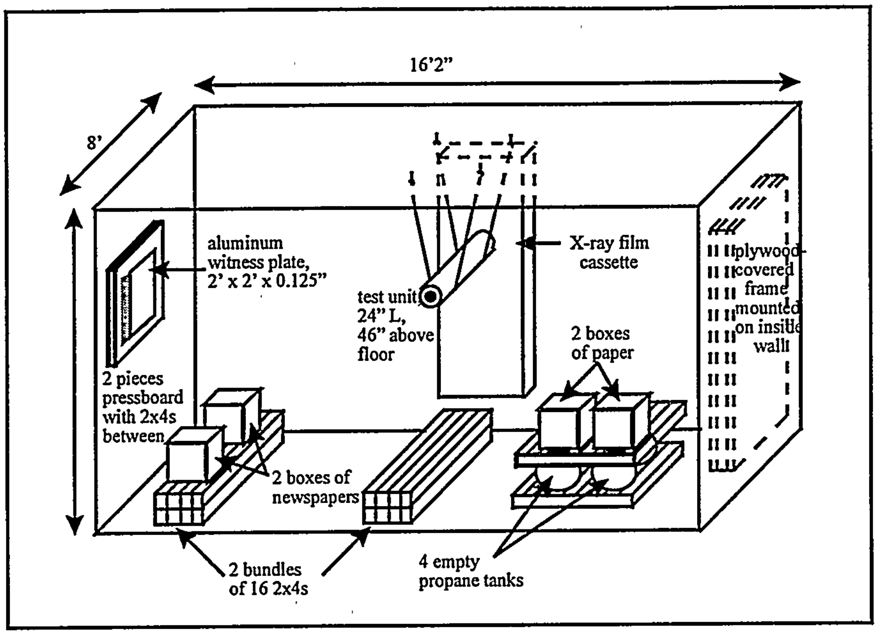

Figure 3. Arrangement in the test cell used for the full-scale penetrator tests.

Experimental Results

The experimental results are listed in Table 1.

Data tabulated for each experiment include:

- the material and dimensions of the metal sleeve or casing;
- the type, density, % TMD, and mass of the fill material (if present);
- the type, dimensions, number, and mass of the explosive pellets used; and
- the ratio of the mass of nonexplosive material to that of explosives (M/C).

The results and comments are listed in the last column.

Fires were started inside the test cell in tests using zirconium in the forms of washers, gravel, and sponge. Following the detonation of the explosives, the burning zirconium was dispersed throughout and outside the test cell. The wood in the test cell was fractured and splintered, which enhanced ignition qualities. In Test 23, fires were started up to approximately 70 meters away from the test cell.

In the full-scale tests, the case broke up in a unique pattern that led to a very large number of fragments. This was due to the axially segmented porous zirconium sleeve. By changing the configuration of the explosive and the incendiary fill, fragment size and shape can be tailored to a given application without compromising the integrity of the penetrator case.

Table 1 - Test Results

test #	date of test	metal sleeve/casing				fill material				HE pellets			M/C ratio[1]	results/comments
		material	OD, in	ID, in.	L, in.	material	ρ, g/cm³	%TMD	wt, g	HE	OD, in.	wt, g		
1	8/9/94	Al	2.5	0.375	3.375	none	---	---	---	PETN	0.5	9.63[2]	~74	burning streamers; several large pieces recovered
2	8/9/94	Mg	2.5	0.375	3.375	none	---	---	---	PETN	0.5	9.63[2]	~49	smaller pieces; no evidence of combustion
3	8/10/94	Mg	1.5	0.625		none	---	---	---	Comp C-4		29[2]		sooty cloud due to C-4 explosive; glowing particles; small melt marks on Lexan; small pieces (<1/16") recovered
4	8/10/94	Mg	2.5	0.75		none	---	---	---	HNS		40.95[2]		no combustion
5	8/10/94	plastic				Ti powder (0.030 ϕ)			30	PBX-9501		3.0[2]	~10	Ti pellets secured in a small plastic container; many hot particles, some hitting Lexan shield
6	8/10/94	Zr	3.0	0.75		none	---	---	---	PBX-9501		49.29[2]		detonator at each end; many particles, more damage; ~1-in particles hot after 10 min
7	8/11/94	Zr	3.0	1.0		none	---	---	---	PBX-9501		96.7[2]	23.5	1 detonator; many burning pieces; m_{Zr}/m_{HE} ~23.5; paper set on fire

[1] M is the total mass of nonexplosive material (e.g., the sum of the masses of the casing and fill material); C is the mass of explosive used.
[2] Total explosive weight.
[3] Explosive weight of interior pellets only.

Table 1 (continued)

test #	date of test	metal sleeve/casing				fill material				HE pellets			M/C ratio[1]	results/comments
		material	OD, in	ID, in.	L, in.	material	ρ, g/cm³	%TMD	wt, g	HE	OD, in.	wt, g		
8	9/7/94	Al Coke can			4.0	Ti sponge		---	416	PETN	0.5	20.72[2]		PETN pellets held in plastic tube; RP-2 detonator; can hung 30 in above floor; burning Ti particles
9	9/7/94	1018 steel	3.0	2.0	3.375	Ti sponge	0.99	22%	215	PETN	0.5	20.72[2]	~93	PETN pellets held in plastic tube; burning Ti and explosively compacted Ti recovered
10	9/8/94	1018 steel	3.0	2.0	3.375	Ti sponge	0.94	21%	206	PBX-9404	0.75 (4)	52.6[2]	~36	PBX-9404 pellets held in plastic sleeve; burning Ti and explosively compacted Ti recovered
13	9/22/94	1018 steel	3.0	2.0	3.375	Zr lumps (pressed)	2.69	42%	589	PBX-9404	0.75 (3)	42.2[2]	~55	three PBX-9404 pellets with 2 booster pellets; more vigorous burning of papers for ~5 min
14	10/3/94	4340	3.0	1.75	6.0	Zr washers	5.95	93%	1081	PBX-9501	0.75 (6), 1.0 (2)	127.3[3]	37	interior pellets extended beyond the ends of the casing; paper set on fire; lots of fragment damage (embedded in wood, a few welded to steel); unreacted Zr recovered

[1] M is the total mass of nonexplosive material (e.g., the sum of the masses of the casing and fill material); C is the mass of explosive used.
[2] Total explosive weight.
[3] Explosive weight of interior pellets only.

Table 1 (continued)

test #	date of test	metal sleeve/casing				fill material				HE pellets			M/C ratio[1]	results/comments
		material	OD, in	ID, in.	L, in.	material	ρ, g/cm³	%TMD	wt, g	HE	OD, in.	wt, g		
15	10/4/94	4340	3.0	1.75	6.0	Zr sponge	3.8298	60%	612	PBX-9501	1.0 (6)	142.1[3]	30	fireball saturated video for 1.2 s; fewer hot particles seen; paper blown away by blast, all burned; plywood ignited after ~1 s
17	10/12/94	1018 steel	3.0	2.0	3.375	Zr sponge	3.9308	61%	381	PBX-9404	0.75 (3)	40.0[3]	52	interior pellets recessed at one end; initiated at the flush end; many glowing particles; paper started to burn at 5 ms, wood at 50 ms, strong fire put out after 10 min
20	11/4/94	4340	3.0	1.75	6.0	Zr sponge	3.60	56%	651	LX-15	1.0	135.1	32	lots of hot particles seen bouncing in the box and spraying out; paper fires started; casing was broken into large pieces
21	10/5/95	4340	4.0	2.0	24.	Zr sponge	4.03	63%	2179	Comp. C-4	~1.5	1106	28	many fragments (>1000) ~11 g; some larger, many smaller; fragment velocity ~1480 fps (1543 fps from Gurney); very strong fire throughout test cell

[1] M is the total mass of nonexplosive material (e.g., the sum of the masses of the casing and fill material); C is the mass of explosive used.
[2] Total explosive weight.
[3] Explosive weight of interior pellets only.

Table 1 (continued)

test #	date of test	metal sleeve/casing				fill material				HE pellets			M/C ratio[1]	results/comments
		material	OD, in	ID, in.	L, in.	material	ρ, g/cm³	%TMD	wt, g	HE	OD, in.	wt, g		
22	10/16/95	4340	4.0	2.0	24.	Zr sponge	4.01	63%	3018	Comp. C-4	~1.25	806	40	much larger fragments; fragment velocity ~1125 fps (1275 fps from Gurney); fires started
23	10/19/95	4340	3.0	2.0	18.	Zr sponge	4.03	63%	2799	Comp C-4	~1.0	371	32	fires visible as soon as smoke cleared; most of Zr ejected out of test cell; large pieces of Zr found in test cell; fragment velocity 1450 fps from Gurney

[1] M is the total mass of nonexplosive material (e.g., the sum of the masses of the casing and fill material); C is the mass of explosive used.
[2] Total explosive weight.
[3] Explosive weight of interior pellets only.

Discussion

The feasibility of coupling additional effects with an explosive device has been demonstrated in these tests. The performance depends on a number of parameters. We have observed the effect of changing some of the parameters, but much more needs to be done to validate our conclusions and to optimize the design of an explosive device with additional effects due to the addition of unconventional energetic materials.

One important parameter is the type of explosive used. The formulation, density, oxygen balance, and detonation properties of the explosives used in the tests are summarized in Table 2. HMX, which was used in Gurney and hydrocode calculations (discussed below), is also listed. The explosive properties are from Dobratz and Crawford 1985, Kinney and Graham 1985, and Mader 1979.

Table 2. Explosive Properties

explosive designation	explosive composition		density, g/cm^3	oxygen (O) balance	detonation properties	
	ingredients	wt %			P, kb	D, mm/μs
Comp C-4	RDX di(2-ethylhexyl) sebacate polyisobutylene fuel oil	91 5.3 2.1 1.6	1.65[1]	very O deficient	257[2]	8.37
HMX	---	---	1.84[1]	slightly O deficient	390	9.11
HNS	---	---	1.72[1]	very O deficient	200[2]	7.00
LX-15	HNS-I Kel-F 800	95 5	1.75[3]	very O deficient	188[2]	6.84
PBX-9404	HMX NC (12.0% N) CEF	94 3 3	1.84[1]	O deficient	375	8.80
PBX-9501	HMX Estane BDNPA-F	95 2.5 2.5	1.84[1]	slightly O deficient	363[2]	8.83
PETN	---	---	1.76[1]	balanced	335	8.26

The power of the detonation, indicated by the detonation pressure and velocity, is an important characteristic for the design of the explosive device. Gurney and hydrocode calculations, discussed below, were done with HMX as the explosive, which has very high

[1] Nominal density.

[2] Calculated detonation pressure.

[3] Theoretical maximum density.

detonation pressure and velocity. PBX-9404 and PBX-9501 are 94 to 95% HMX and are the most powerful explosives we used in these tests. LX-15 is a much less powerful explosive. The effect of the power of the explosive can be seen by comparing Tests 15 and 20, both of which contained zirconium sponge as the combustible fill material. In Test 15, PBX-9501 pellets were used. The casing was broken into small pieces, the zirconium was well dispersed, and the wood in the test cell was ignited. In Test 20, which used LX-15 pellets of the same diameter as the PBX-9501 pellets in Test 15, the casing was broken into very large pieces, much of the zirconium was found unreacted and in large explosively compacted pieces, and none of the wood was ignited. This effect is even more noticeable in a comparison of Tests 17 and 20. In Test 17, even though the PBX-9404 pellets were 0.75 inches in diameter and there was only about 30% as much zirconium as there was in Test 20, the wood ignited and grew into a vigorous fire that had to be extinguished by test personnel.

Also tabulated in Table 2 is the oxygen balance of the explosive. Oxygen-rich explosives show molecular oxygen in the nominal products and generate little smoke or soot. Oxygen-deficient explosives show combustible products such as carbon, carbon monoxide, or hydrogen and generate large amounts of smoke or soot. Oxygen-balanced explosives show oxidized products such as CO, CO_2, and H_2O. We used the highest oxygen-balanced explosives available for our tests when possible; with less smoke and soot the video coverage was better. This made it possible to view ignition and burning after the explosive was detonated. This is why Comp C-4 was not used in most of the tests, even though it may be the explosive of choice for certain applications. (Comp C-4 was used in the full-scale tests because of time constraints.)

The products of oxygen-rich explosives may also assist in the ignition and burning of the combustible fill. To determine if this affected the ignition of the zirconium, we performed Test 20 with LX-15 explosive pellets and zirconium sponge fill material to compare to Test 15, which was done with PBX-9501 pellets. LX-15 is an oxygen-deficient explosive and produces less of the oxidized products (e.g., steam and CO_2) that would aid the ignition of the zirconium particles. Although the one-inch-diameter LX-15 pellets did not disperse the zirconium well, there were many visible burning particles in the videotape coverage of Test 20. This indicates that the zirconium can function well as an incendiary with an oxygen-deficient explosive.

Zirconium performed the best as an incendiary in the tests discussed here. We obtained the best results from zirconium sponge, but zirconium in the form of thin disks also performed well. In Test 14 with 3-mm-thick zirconium disks, the wood was scorched but did not burn. Large partially reacted pieces of zirconium were recovered. These larger fragments penetrated the wood, scorching the wood but not depositing enough energy for ignition. Modifications such as scoring the washers, using thinner washers, and changing the amount and type of explosive used should be considered.

Fragment velocities were calculated for the last three tests using the Gurney method (Henry 1967, Kennedy 1972) with some modification. The Gurney method assumes that the potential energy in the explosive charge before detonation is equal to the kinetic energy of the charge and casing after detonation and expansion. In the calculations done here, the energy used to compact the porous zirconium was subtracted from the Gurney energy for the explosive. The predicted fragment velocities agreed within 5% of the measured fragment velocity measured in Test 21 and 13% of that measured in Test 22.

Conclusion and Recommendations

The experiments described in this report have demonstrated the feasibility of adding enhanced effects to an explosive device by the addition of combustible metals.

The incendiary performance depends on a number of parameters. From the tests described here, we have come to the following conclusions:

- there must be enough explosive (the amount needed depends on the detonation properties of the explosive) to adequately break up the casing and disperse the combustible fill material in effective particle sizes;
- the monolithic test configuration, with a thick-walled sleeve of combustible metal, does not work well as an incendiary;
- zirconium was the best incendiary material;
- the breakup of the material in the test cell due to blast and fragmentation contributed to the ignition process.

Additional work needs to be conducted to optimize the choice of materials, relative amount of explosive, and penetrator configuration. If the combustible fill is porous, more explosive may be needed to attain fragment damage. For the combustible fill materials, other metals, such as a mixture of zirconium and aluminum which exothermically alloy, may further enhance the incendiary effect.

We recommend that future experimental work include the following:

- additional tests with zirconium washers to better determine incendiary performance;
- optimization of the type, amount, and oxygen balance of the explosive;
- optimization of the type, morphology, and density of the combustible fill material;
- tests with other combustible metals and intermetallic compositions.

Our results indicate that a metalized incendiary explosive device is feasible and capable of starting massive fires at the target site.

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