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Trends in Explosive Contamination*

ABSTRACT: This study sought to assign a rough order of magnitude for the amount of explosive residue likely to be available in real-world searches for clandestine explosives. A variety of explosives (TNT, TATP, HMX, AN, RDX, PETN) in various forms (powder, flake, detonating cord, plastic) were carefully weighed or cut into containers, and the amount of residue inadvertently remaining on the work area, hands, or containers was quantified. This was used to evaluate the spillage potential of each explosive. The adhesion of each explosive to a glass surface was quantified from amount of explosive adhering to the inside of a glass vial into which the explosive had been placed and then removed by vigorous tapping. In powdered form, most of the explosives—TNT, PETN, RDX, HMX, and TATP—exhibited similar spillage and adhesion to glass. However, PETN as sheet explosive and plasticized RDX (C-4), showed very little potential to contaminate surfaces, either by spillage or adhesion to glass.

KEYWORDS: forensic science, explosive contamination, explosive residue, explosive analysis, TNT (2,4,6-trinitrotoluene), AN (ammonium nitrate), PETN (pentaerythritol tetranitrate), TATP (triacetone triperoxide), RDX (hexahydro-1,3,5-trinitro-s-triazine), HMX (octahydro-1,3,5,7-tetranitro-1,3,4,5-tetrazocine), C-4, sheet explosive

Spillage and adhesion of low volatility particulate material during the construction of improvised explosive devices (IED) offer important avenues for chemical detection. Since the majority of solid explosives have extremely low vapor pressures, detection relies on the use of swabbing or vacuuming methods (1–5). Swabbing procedures may pick up small, sticky particles but not with great efficiency, while vacuuming tends to collect large, bulky and weakly adhering particulates (6). With detection techniques being stepped up at airports and other public locations, it is important to know how much residue might possibly be available for detection. Presumably the prevalence of explosive residue depends on the care taken by the bomb assembler, but it may also be intrinsic properties associated with the explosive. To test this hypothesis, we gathered a group of chemists of various degrees of experience and asked them to handle small quantities of explosives under controlled conditions. A protocol was formulated where hands and work areas were swabbed before and after explosive handling. In addition, glassware purposely exposed to specific explosives was analyzed to evaluate adhesion to the surface. Six different military explosives, in various physical forms, were considered: nitramines (HMX, RDX, RDX detonating cord and C-4); nitrate ester (PETN powder, cord, and sheet explosive); nitroarene (TNT in powdered and flaked form); along with the improvised explosive triacetone triperoxide (TATP) and ammonium nitrate (AN), the main ingredient of most commercial formulations. The chemical structures of the explosives are shown in Fig. 1 together with their melting points.

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Experimental Section

PETN crystalline particles were about 0.3 mm in diameter, and noticeably free-flowing, like dry table salt. The crystalline particles of reagent grade AN were translucent and larger than PETN (~1 mm); as AN picked up water, the grains tended to aggregate. RDX and HMX were fine white powders in the size range of 25 to 100 micron. They had similar morphology and visibly adhered to the glass walls of the containers in which they were stored. TATP was a white, microcrystalline material of slightly smaller particle size than PETN. The TNT powder was beige in color; it was very fine and tended to clump together and adhere slightly to its glass container. A second batch of coarser flaked TNT was also used; it appeared to be a mixture of powdered TNT and crystals as large as 1 mm in diameter. The detonating cords and plastic explosive were supplied by Ensign Bickford. The PETN cord (Primacord) was 50 grain per foot of cap-grade PETN wrapped in a yellow jacket of low-density polyethylene; polyester yarn, and wax coating (approximate o.d. 5.2 mm, i.d. 4 mm). The RDX cord was 80 grains per foot; the pink-tinted RDX was a mixture of class 5 and 7 RDX (58.9% explosive by weight) with Natrosol binder (hydroxyl ethyl cellulose), and Crayola red dye. The black jacket had a polyester braid interior with Nylon/carbon black color concentrate exterior (about o.d. 5.2 mm, i.d. 4 mm). The gray PETN sheet (Primasheet) was 2 mm thick; its composition was about 63.5% PETN, 8% nitrocellulose, 28.4% plasticizer (Citraflex) and traces of carbon black, ferric oxide, and the required taggant DMNB (2,3-dimethyl-2,3-dinitrobutane). C-4 was provided by the FAA; it was a white, putty-like lump made of 91% RDX, 2.1% polyisobutylene, 1.6% motor oil, 5.3% di-2-ethyl hexyl sebacate or adipate with 0.1% taggant DMNB added to the mixture.

Test Protocol

For each test (a test being one explosive and one participant), four feet of the laboratory bench on either side of a balance (Met-

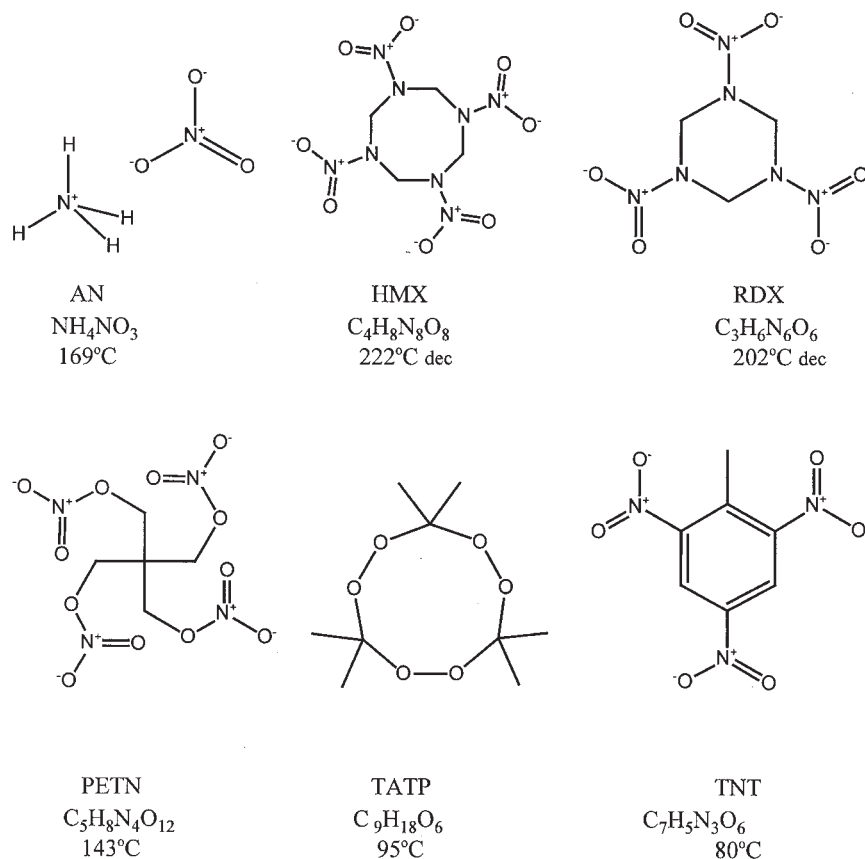


FIG. 1—Chemical structures and melting points of the explosives used in this study.

tlar AT200) was cleaned with soap and water, acetone, and methanol. The balance platform and pan were cleaned with a damp cloth (water then acetone). Two controls were obtained prior to each test. First, each participant washed his hands with soap and water, then swabbed the laboratory bench area and the balance platform and pan with acetonitrile and placed the swab in a labeled test tube. Second, the participant swabbed his hands with acetone and placed the swab in another labeled test tube. Either cotton balls pre-cleaned by the DSTL Forensic Explosive Laboratory or Whatman No.1 (11.0 cm diameter) filter paper was used.³ For each test the participant was provided with five empty glass receiving vials (15 mm \times 45 mm, 1 dram) (13 mm \times 44 mm, 18.0 cm² surface area), ten labeled test tubes (15 cm \times 1.8 cm), a small spatula, two forceps, clean cotton swabs or filter paper, a small amount of swabbing solvent [(acetonitrile or acetone (hands))], a record sheet and pen. If the test involved powdered explosives (TNT, PETN, ammonium nitrate, RDX, HMX, TATP), a glass screw-cap vial containing about 0.5 g of explosive (stock vial) and a precut square of aluminum foil (8 cm \times 8 cm) were also provided. The aluminum foil was positioned on the balance pan and tared with an empty re-

ceiving vial. The participant transferred approximately 0.1 g of explosive from the stock vial into the receiving vial and recorded the weight. The receiving vial was removed from the balance leaving the foil in place. The contents of the receiving vial were returned to the stock vial by inverting the vial and tapping gently. Then, the "used" receiving vial was placed in a labeled test tube. The participant weighed out four more samples into receiving vials, repeating the weighing/transferring procedure. After the fifth and final transfer, the aluminum foil was removed from the balance pan and carefully placed in a labeled test tube. The participant again swabbed the work area and his hands for explosive residue and placed the swabs in labeled test tubes. For plastic, sheet and cord explosives [RDX cord, PETN cord (Primacord), PETN sheet, and C-4], the participant was given a clean aluminum plate and a single-edged razor blade to cut the materials. Participants were asked to cut the detonating cord into approximately 5 mm segments and the PETN sheet (Primasheet) and flattened C-4 into about 2 mm widths. Each cut piece (five in all) was placed in a separate receiving vial (without weighing) and then discarded into a disposal vial. The blade and metal cutting plate were rinsed, rather than swabbed; otherwise, the protocol closely followed that of the powdered explosive. Ambient relative humidity ranged from 20% to 100% during the course of this study.

Quantitative Chemical Analyses

TATP and HMX residues were extracted with acetone while ammonium nitrate residues were extracted with water. The remaining explosive residues were extracted with acetonitrile. The extraction

³ DSTL, the British Defence Science & Technology Laboratory, prepared the cotton swabs by Soxhlet extraction with water followed by two extractions with acetone and vacuum drying. The dry swabs were sealed into nylon bags until ready for use. Whatman No. 1 paper used directly from the box was later found to be clean and free of background signal with electron capture detection (gas chromatography) and photodiode array detection (liquid chromatography). It was as effective for swabbing purposes as the cotton swabs. Once this was realized we tended to use the filter paper since less preparation was involved.

methods for the vials and swabs were the same for all the explosives. Four of the receiving vials were extracted with 10 mL of solvent (one was retained in case further analysis was required). The aluminum foil, pre- and post-swabs of hands and work area were extracted with 3 mL of the same solvent, and the outside walls of the stock vial was rinsed with about 5 mL of the solvent. The extracts (10 mL) of the receiving vials were diluted 10 to 1, and 2 mL of the dilute solution was transferred to Agilent 2 mL crimp cap auto-sampler vials and sealed. The extracts of the swabs and foil were used without dilution; 2 mL were transferred to auto-sampler vials and sealed. The rinses from the walls of the stock vials were concentrated to a volume of 2 mL and the concentrate transferred to auto-sampler vials. The quantitative chemical analysis used for each type of explosive is described below.

TNT, RDX, PETN, and TATP

A Hewlett Packard (HP) model HP5890 gas chromatograph (GC) equipped with a J&W DB-5MS (6 m × 0.53 mm I.D., 1.5 μm film) column and electron capture detection was used. For TNT the injector temperature was 250°C and the detector temperature was 300°C. The oven temperature was held at 100°C for 30 seconds and ramped to 120°C at 2°C per minute; next it was raised at 3°C per minute to 135°C and finally, at 20°C per minute, to the final temperature of 300°C. For RDX, PETN and TATP the injector temperature was 165°C and the detector temperature was 300°C. The oven temperature was held at 50°C for 2 min and ramped at 20°C per minute to a final temperature of 280°C. External standards were used for quantification. Standard curves of at least 4 data points in the concentration range 1–20 ppm were constructed for each of these explosives; all were linear with squared correlation coefficients of at least 0.99. Actual samples, usually containing much higher concentrations, were diluted until their response was in the concentration range of the standard curves. Actual amounts were then calculated from the dilution factor.

HMX

A HP 1100 liquid chromatograph with photodiode array detector ($\lambda = 234$ nm) and HP Hypersil BDS C-18 (100 × 4 mm, 3 μm particle size) column was used. The mobile phase consisted of methanol and water at a flow rate of 0.25 mL per minute. The initial concentration was 15 % methanol held for 3 min. The methanol concentration was then increased linearly to 55% over a 2-min interval. The column was re-equilibrated (15 min) with 15% methanol between runs. Standard curves of at least 4 data points in the concentration range of 1–20 ppm were constructed; curves were linear with squared correlation coefficients of at least 0.99. Actual samples, usually containing much higher concentrations, were diluted until their response was in the concentration range of the standard curves. Actual amounts were then calculated from the dilution factor.

C-4

A HP 1100 liquid chromatograph with photodiode array detector ($\lambda = 234$ nm) and HP Hypersil BDS C-18 (100 × 4 mm, 3 μm particle size) column was used to detect the RDX from C-4. The mobile phase consisted of methanol and water at a flow rate of 0.72 mL per minute. The initial concentration was 26 % methanol. The methanol concentration was increased linearly to 35.8% over a 7-min interval, followed by an increase in methanol concentration to 70% over a 1 min interval. It was held at 70% methanol for 2 min. The column was re-equilibrated (15 min)

with 26% methanol between runs. Standard curves of at least 4 data points in the concentration range of 1–20 ppm were constructed; curves were linear with squared correlation coefficients of at least 0.99. Actual samples, usually containing much higher concentrations, were diluted until their response was in the concentration range of the standard curves. Actual amounts were then calculated from the dilution factor.

Ammonium Nitrate

A Thermo Separations Constametric 3200 pump, with a Waters 431 conductivity detector and Waters IC-Pak Cation M/D (3.9 mm × 150 mm) column were used with an isocratic mobile phase consisting of 29.2 mg of EDTA and 189 μL of concentrated nitric acid in 1 L of water. The flow rate was 1.00 mL/min. Standard curves of at least 4 data points of concentrations ranging from 10–200 ppm were constructed; all were linear with squared correlation coefficients of at least 0.99. Actual samples, usually containing much higher concentrations, were diluted until their response was in the concentration range of the standard curves. Actual amounts were then calculated from the dilution factor.

Results

Tables 1–3 give results by participant for three of the explosives in this study. Eight similar tables were constructed for the rest of the explosives examined; these are shown in the Appendix. Out of over a thousand data points, seven were deleted from the averaging due to very large deviations; four of the six were excessive spills on the laboratory bench (see Tables in Appendix). Table 4 summarizes the average results for each of the eleven explosives tested. Columns 1 and 2 in Table 4 gives the average micrograms (from individual tables, i.e., Tables 1–3) of explosive detected on the bench top and balance pan and on the participants' hands prior to starting the test. These controls usually yielded no detectable explosive material. However, RDX powder and cord and TATP exhibited slight contamination. We speculate these anomalies could be attributed to significant contamination of the bench area prior to cleaning or intrinsic persistence of these materials for the bench top surface.

The data in the remaining columns was considered in two groupings: columns 3–6 and columns 7–10. Columns 3 through 6 give the micrograms (Tables 1–3) or average micrograms (Table 4) of explosives accidentally left in the indicated areas after manipulation of the explosive. Column 4 was for the bench top and balance pan; and column 5, the hands at the end of the manipulation. For powdered explosives, column 3 is the amount of explosive spilled on the aluminum foil covering the balance pan and column 6 the residue on the outside of the stock vial. For cut explosives (cord and plastic) column 3 is the explosive left on the aluminum cutting plate and razor blade, while column 6 indicates the residue on the outside of the disposal vial where the cut explosive pieces were dumped from the receiving vials. The residue indicated in columns 3 through 6 is not the total residue found, just the amount found in a typical swabbing exercise. Columns 7 to 10 show the *total* micrograms of explosive adhering to the inner glass surface of the four receiving vials.

Table 4 summarizes the results of Table 1 through 3 and similar tables prepared for each explosive (see Appendix). It shows the average micrograms of explosive found in each location, along with the standard deviation for each. The values found in columns 3–6 are affected by the swabbing technique, the skill of participant, and the type of explosive handled. The values averaged from 40 vials (10 participants with 4 vials each) should be much less affected by

TABLE 1—Micrograms (μg) of residual, powdered TNT (swabs).

Column	1	2	3	4	5	6	7	8	9	10
Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
E	ND	ND	17	ND	ND	0.42	197	221	213	208
G	ND	ND	10	5	0.10	ND	171	159	148	172
D	ND	ND	ND	2	0.14	5	160	153	161	155
F	ND	ND	39	17	0.24	3	207	206	223	209
K	ND	ND	ND	ND	0.33	0.78	138	154	153	158
B	ND	ND	67	2	1.2	7	195	206	218	189
A	ND	ND	53	ND	2.0	5	214	189	197	204
J	ND	ND	133	6	4.0	7	179	174	183	174
C	ND	ND	101	1	6.3	13	196	215	232	232
H	ND	ND	9	4	9.8	9	176	190	198	177
	Average		54	5	3	6			average =	188
	std. dev.		45	5	3	4			std. dev.	25

Columns

0—Code of participant in the study.

1—Lab bench after cleaning, before start of experiment. For powdered explosives balance pan was included.

2—Participant's hands after washing, before start of experiment.

3—Aluminum foil on balance pan in powdered explosives or Al plate on which explosives (cord) was cut.

4—Lab bench at end of experiment. For powdered explosives balance pan was included.

5—Participant's hands at end of experiment.

6—Rinse of outside of stock vial from which powdered explosives were taken or into which cut explosives were placed.

7–10—Individual vials into which powdered explosives were weighed or cut explosives placed.

TABLE 2—Micrograms (μg) of residual, powdered RDX (filter paper).

Column	1	2	3	4	5	6	7	8	9	10
Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
L	ND	0.13	392	79	4	9	416	400	417	458
E	0.30	0.05	25	4	4	7	370	393	423	396
O	7.13	0.10	557	116	4	60	461	406	463	646
D	0.23	0.30	104	24	10	6	383	410	379	385
V	0.32	0.14	756	113	12	73	358	445	336	301
W	ND	0.36	321	341	29	6	473	491	525	598
F	0.91	0.30	111	116	36	3	344	412	325	370
G	0.14	0.21	138	195	36	18	251	325	275	334
C	5.24	0.25	20	109	80	30	482	448	530	612
A	ND	0.32	42	8	89	61	376	371	292	245
	average	0.22	123	179	70	29			average =	408
	std. dev.		253	100	31	27				91

TABLE 3—Micrograms (μg) of residual, crystalline PETN (filter paper).

Column	1	2	3	4	5	6	7	8	9	10
Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
T	ND	ND	2827	370	ND	ND	171	1077	686	529
U	ND	ND	1434	34	0	1	179	340	267	275
P	ND	ND	3825	420	0	33	1280	432	1194	471
Q	ND	ND	3644	33	1	15	746	128	365	657
E	ND	ND	4	36	4	24	201	438	178	244
D	ND	ND	4101	172	7	5	366	160	175	147
G	ND	ND	3689	51	8	28	72	44	322	59
R	ND	ND	ND	34	10	ND	177	1788	628	3120
F	ND	ND	2078	844	36	53	432	328	255	248
A	ND	ND	2750	12	67	7	167	104	76	85
	average		2706	201	15	21			average =	465
	std. dev.		1340	271	22	17				570

TABLE 4—Average of micrograms of residual explosive.

Columns # Tab 1–3 Explosive	1 & 2		3		4		5		6		7–10	
	Hands & Bench Begin	Al Foil* END	Std Dev	Bench END	Std Dev	Hands END	Std Dev	Outer Vial END	Std Dev	Receiving Vials	Std Dev	
AN	ND	6254	11456	742	1472	895	1325	37	37	4318	4124	
HMX	ND	1356	1089	234	379	19	21	13	11	535	399	
PETN	ND	2706	1340	201	271	15	22	21	17	465	570	
PETN cord	ND	1594	*620	221	349	13	18	41	67	440	509	
RDX	1	123	253	179	100	70	31	29	27	408	91	
TATP	1	1539	1822	259	444	11	18	16	45	268	458	
TNT	ND	54	45	5.2	5	2.7	3	5.7	4	188	25	
TNT flake	ND	34	22	12	15	2.2	2	3.1	2	174	12	
RDX cord	1	127	*31	417	262	22	21	1	0.3	174	207	
PETN sheet	ND	40	*33	0	0	3.6	5.9	4.3	6.2	1.5	1.4	
C4 (RDX)	ND	115	*129	ND	ND	ND	ND	ND	ND	ND	ND	
Average		1383		227		105		17		697		
Average–AN		841		170		18		15		295		

Averages in columns 1–6 are of 10 data points. Average for vials (columns 7–10) are of 40 data points.

* For weighed explosive value in μg on Al foil; for cut explosive it is μg on knife blade and cutting plate.

“Average–AN” is the average without the results for AN.

the skill of the individual participant and more dependent on the adhesion properties of the explosive since explosive was purposely placed in each receiving vial and then dumped out with tapping. Examining the average micrograms found in the receiving vials (columns 7–10), a significant trend is evident. Most explosives (HMX, TNT flaked or powder, PETN cord or powder, RDX cord or powder, and TATP) left from 100 to 500 μg of explosives in the vials; AN left a factor of ten more, while PETN sheet and C-4 left a factor of 100 less. The average values found for each explosive in the swabbed areas (columns 3 to 6) showed similar (i.e., AN left the most; PETN sheet and C-4, the least, residue), but not identical trends. The amounts of residual explosive varied dramatically among the four areas. The aluminum foil, over which weighing was done (powdered explosive) or plate on which cutting was performed (cord or plastic), had the highest amount of residual explosive. Second in amount was the laboratory bench. The hands and the outside of the explosive stock vial generally had an order of magnitude less explosive than the bench, with the exception of AN.

To assess the variability, in one series, flaked TNT, the receiving vial portion of the study was completely re-run a few weeks after the first series. The average of the forty receiving vials in the first series was 101 μg ; in the second series it was 174 μg . Thus, the magnitude of variability was about 75%, which may result from variations in humidity but, in any case, is not much larger than the standard deviation reported for most individual series. To determine the effect of the amount of explosive weighed into the receiving vials, 1000 mg (instead of 100 mg) of flaked TNT were added to and removed from 40 receiving vials. The average amount of TNT left adhering to the vials was 5633 μg with standard deviation of about 11% (compared with 174 μg , with 12% standard deviation, when 100 mg were used). To examine the effect of the surface area of the vials, 100 mg of flaked TNT were weighed into and removed from larger sample vials—surface area 31.1 cm^2 (23 mm dia. \times 43 mm)—instead of the usual 18.0 cm^2 . While the actual aliquot of explosive contacted slightly less glass while sitting in the larger vial, during the removal process, it contacted about twice as much glass surface as an aliquot of the same weight in a 13 \times 44 mm vial, due to its near doubling of diameter. The average amount of TNT remaining in the larger vial increased from 174 μg to 2243 μg .

Discussion

It was assumed that participants would demonstrate different skill levels in the performance of the trials, particularly in the four areas where they had the greatest opportunity to spill explosives. The primary area, aluminum foil covering the balance pan (powdered explosive) or the aluminum cutting plate (cord or plastic explosive), registered the highest amounts of residue, averaging about 841 μg (excluding AN data). The bench, also an area of primary contamination averaged about 20% that of foil or cutting plate. Excluding the AN data, the areas of secondary contamination, hands and the outside of the stock vials (Table 4), accounted for about 2% of the explosive (18 and 15 μg , respectively) compared to direct exposure (i.e., the aluminum covering). Because the main mechanism for contamination of the outside of the stock vial were the hands of participants, it was surprising that the amount of explosive residue found on each was comparable.

The amount of explosives found in swabbed areas (columns 3–6) to some extent followed the trends observed in the receiving vials (columns 7–10, Table 4). However, there were sufficient deviation from the trend to suggest one or more additional factors should be considered. The most obvious was the fact that the physical size and shape of the explosive particles made them more or less easy to spill from the spatula. In considering “spilling from a spatula,” there was definitely the participant factor to consider since some people were inherently more prone to spillage than others. Because for each explosive the same set of 10 people was not necessarily used, it seemed likely there was little participant factor involved in these numbers. The repeated experiment placing and removing flaked TNT in receiving vials had only five participants in common with the first study, and it gave results of the same order of magnitude (101 μg vs 175 μg) as the first. Nevertheless, further examination of a possible “participant effect” was performed by evaluating the micrograms of explosive found on a participant-by-participant basis. Table 5, prepared for participant A, is exemplary of the tables constructed for each participant. These tabulate the number of micrograms of explosive found in each area for each explosive examined by the participant. These values were then divided by the overall average for that area and that particular explosive (values found in Tables 1–3, etc.). The participant received a

“1” in a category if his result was average for that explosive. Since the participants were involved in different numbers of tests, the “Table 5” for each would vary in length. To compare the participants with each other, the averages in Table 5 were averaged (bottom line in Table 5). Table 6 tabulates the average of these averages for each participant and lists the number of gender, years of experience, and number of tests for each participant. Again, a perfectly average score is “1”. It can be seen that overall there is little difference among the participants and there is little correlation with the participant’s gender or years in the lab or number of tests performed in this study.

As noted earlier, the trends observed with explosives adhering to the receiving vials (columns 7–10) are similar to those that reflect spillage (columns 3–6, Table 4). If an explosive adhered strongly to the interior of the glass vial, the participant had a higher probability of spilling or inadvertently transferring it to the surroundings. Adhesion of an explosive is governed by both macroscopic mor-

phology and complex physical sorption processes. PETN sheet explosive and C-4 are imbedded in a matrix that prevented adhesion of the explosive, itself, to the glass walls of the vials. They are also least likely to be spilled. The sheet explosive is less than 64% PETN, and the PETN is embedded in nitrocellulose and plasticizer. Apparently, manipulation or touching the flexible polymer transfers very little PETN—hence little spillage. This also ensured small particles of PETN were not left adhering to the glass of the receiving vials. Had an entire strip of explosive adhered to the glass, the participant would easily have detected and removed it. The same argument can be made for C-4 which is about 91% RDX. For C-4 no RDX was detected in any category except the razor blade and cutting plate. A value of 115 μg was essentially identical to that found for RDX powder and cord [123 μg and 127 μg , respectively] on aluminum foil (Table 4). In this series of tests, C-4 clearly exhibited least adhesion and spillage. Initial data for TATP also indicated extremely low adhesion and spillage. However, it was found

TABLE 5—Normalized results in each area for participant A.

Person	Explosive	Al Foil	Bench End	Hands End	Stock Vial	Average Spill	Receiving Vials			Average Adhere	
A	TNT	0.99	0.00	0.75	0.83	0.64	1.14	1.01	1.05	1.09	1.07
A	RDX	0.34	0.05	1.26	2.12	0.94	0.92	0.91	0.72	0.60	0.79
A	PETN	1.02	0.06	4.56	0.35	1.50	0.36	0.22	0.16	0.18	0.23
A	HMX	0.13	0.00	0.35	0.48	0.24	1.16	0.43	0.24	0.26	0.52
A	TATP	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.04	0.02
A	PETN cord	0.28	4.13	0.15	2.22	1.70	0.81	0.06	0.01	0.01	0.22
A	PETN sheet	1.52	0.00	0.10	0.24	0.46	0.00	0.00	0.00	0.00	0.00
A	AN	0.00	0.03	0.26	1.26	0.39	0.29	0.29	0.27	0.43	0.32
A	TNT flake	0.15	0.21	0.45	0.50	0.33	0.70	0.89	0.74	0.79	0.78
A		0.49	0.50	0.88	0.89	0.69					0.44

“Normalized Results” refers to the fact that the values were divided by the overall average for that area and that particular explosive (see original values and averages for each area for participant A for TNT, RDX, PETN in Tables 1, 2, and 3, respectively).

TABLE 6—Average of all tests for each participant.

Person	Gender	# Test	Years	Al Foil	Bench End	Hands End	Stock Vial	Average All Spills	Average Vials
G	m	7	3	1.03	0.42	0.37	0.33	0.54	0.36
A	m	10	4	0.49	0.50	0.88	0.89	0.69	0.44
M	f	5	5	1.73	1.38	0.67	0.12	0.98	0.57
U	f	1	2	0.53	0.17	0.01	0.04	0.19	0.57
L	m	6	3	1.36	0.52	0.56	0.67	0.78	0.63
C	m	5	2	0.76	0.30	1.02	0.99	0.77	0.63
F	m	9	9	1.14	2.70	1.72	1.18	1.60	0.71
H	m	2	2	0.53	0.44	1.86	0.80	0.91	0.72
J	f	2	5	1.97	0.76	0.88	0.65	1.07	0.72
K	f	1	5	0.00	0.00	0.12	0.14	0.07	0.80
P	f	7	1	0.93	0.46	0.43	0.53	0.59	0.87
E	m	10	5	0.61	0.23	0.56	0.24	0.43	0.88
Q	f	4	1	1.14	0.35	0.40	1.08	0.74	0.88
V	m	1	2	6.12	0.63	0.17	2.52	2.36	0.88
D	f	8	9	0.64	0.49	0.71	1.95	0.95	0.91
B	m	8	4	0.70	0.62	0.56	0.99	0.72	0.93
W	m	1	2	2.60	1.91	0.41	0.22	1.29	1.28
T	f	1	2	1.04	1.84	0.00	0.00	0.72	1.32
O	f	2	4	2.82	0.34	1.49	1.15	1.45	1.38
S	m	3	1	0.95	2.98	3.61	2.15	2.42	1.50
N	f	7	3	1.84	0.51	0.88	0.26	0.87	2.64
R	f	1	2	0.00	0.17	0.66	0.00	0.21	3.07
Average		4.6	3.5	1.3	0.8	0.8	0.8	0.9	1.0
Std. Dev.				1.3	0.8	0.8	0.7	0.6	0.7

that the high volatility of TATP introduced systematic errors in its quantification. Previously, the FAA laboratory found a weight loss of 1.8% per hour. We observed a loss of no more than 0.9% per hour. This is significant and could lower observed micrograms of TATP by a factor of 2 or 3. The data in Table 4 for TATP represents a repeat test where all samples were sealed and stored in the freezer (-15°C) while awaiting analyses.

The PETN powder and cord, RDX powder and cord, HMX powder, and TATP (if extreme measures were taken to prevent its volatilization) all exhibited a moderate degree of adhesion ($500\text{--}170\ \mu\text{g}$) and spillage. The high propensity for ammonium nitrate to adhere and spill is probably related to its hygroscopic nature. It tended to form clumps and the adhesion of water to glass was likely to play a significant role.

For most explosives, the amount adhering to the inner wall of the glass vials ranged from about $170\ \mu\text{g}$ to $500\ \mu\text{g}$. This represented only about 0.2% to 0.5% of the 100 mg of explosives initially added and then removed from receiving vial. On the aluminum foil, there was as much as $2700\ \mu\text{g}$ of PETN, which is about 3% of the PETN weighed out. Even with relatively careful measuring, spillage is likely to account for a few percent of the total amount of explosive handled while secondary contamination (adhesion to hands, outsides of vials etc.) would be on the order of tenths of percents. Whether these values are scalable is a question for further work. On the laboratory-scale, they were. When the amount of explosive was increased from 100 mg to 1000 mg (flaked TNT), the average amount of TNT remaining in the receiving vials ($5633\ \mu\text{g}$) was still roughly 0.5% of the TNT used. When the surface area of glass exposed to explosive was roughly doubled, the amount of flaked TNT left in the vials increased an order of magnitude. Clearly increasing the surface area available for adhesion, and likely, the surface area swabbed, is critical to increasing the amount of residue detected.

Conclusion

This study examined explosives in different physical states—powder, wrapped powder, microcrystalline, plasticized—and of different chemical classes—nitroarene (TNT), nitramine (RDX and HMX), nitrate ester (PETN), peroxide (TATP), and energetic salt (AN). It quantified explosive residue remaining in the primary work area and in secondary transfer points during simple manipulation operations (weighing and cutting). It also investigated the tendencies of these explosives to adhere to glass. This study also sought to assign a rough order of magnitude for the amount of explosive likely to be available in real-world searches (7). In particular, it examined whether a given explosive, or class of explosives, were more or less likely to be left as residue. Using the constraints of the real-world search, a range of explosive handlers of varying degrees of skill were employed and work proceeded regardless of

relative humidity. The repeat experiments mentioned above for TNT, at different ambient humidities, yielded similar results ($101\ \mu\text{g}$ vs. $175\ \mu\text{g}$) within experimental error. The participant factor was examined in more detail. On an individual test basis, this factor could be extremely important, e.g., a particular participant was prone to spill explosive. However, on an overall basis it was of secondary importance relative to the type explosive handled.

On the scale of this study (milligrams of explosive), we found as much as a few percent of the total amount of explosive being manipulated might remain in the work area. However, secondary contamination (of the hands and what they touch, e.g., outside of the receiving vial) was significantly less (less than tenths of percent). The exterior of containers housing IED might be expected to be contaminated with hundredths of a percent of the total explosive weight.

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Appendix

TABLE 7—Micrograms (μg) of residual HMX, white clingy powder, by filter paper.

Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
N	ND	ND	2357	130	5	ND	574	426	528	374
A	ND	ND	171	ND	7	6.28	620	229	129	138
M	ND	ND	2503	171	11	2.17	534	276	132	339
E	ND	ND	88	ND	11	ND	2013	530	1249	1173
Q	ND	ND	2962	7	15	4.55	375	93.3	903	465
P	ND	ND	1937	100	15	6.86	603	403	578	898
L	ND	ND	50	89	17	17	298	280	33.8	355
S	ND	ND	762	1085	70	36	539	521	527	1148
B	ND	ND	938	60	ND	16	1448	459	377	489
F	ND	ND	1790	6714	ND	16	285	500	320	223
	average		1356	234	19	13			average =	535
	std. dev.		1089	379	21	11				399

Data not included in the average is marked in a box.

TABLE 8—Micrograms (μg) of residual TATP, small, white crystals, by filter paper.

Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
A	ND	ND	ND	ND	ND	ND	0.12	0.27	0.18	0.83
E	ND	ND	0.31	0.51	ND	ND	0.36	1.04	0.56	3.45
J	ND	ND	975	1.6	0.15	ND	0.86	0.98	1.75	42
B	ND	ND	0.17	3.0	0.20	1	0.20	0.24	5.95	0.39
G	ND	ND	1462	2.2	0.25	ND	0.13	0.13	0.19	0.12
D	ND	ND	247	6.6	0.37	5	0.24	2169	4.31	0.24
C	ND	ND	111	2.3	0.39	0	0.49	2.83	3.36	0.17
N	ND	ND	1170	10	0.41	0	196	202	81	330
M	ND	ND	1566	15	0.81	ND	0.22	1.50	0.50	0.88
F	ND	ND	448	1343	2.05	0	0.21	0.13	0.14	0.37
	average		664	5	1	1			average =	23
	std. dev.		634	5	1	2				68

Data not included in the average is marked in a box.

TABLE 9—Micrograms of PETN from Detonating Cord, (0.5 cm cut by blade on metal plate).

Person	Bench Begin	Hands Begin	Plate + Blade	Bench End	Hands End	Disposal Vial	Vial 1	Vial 2	Vial 3	Vial 4
E	ND	ND	1629	ND	0	9	1153	503	345	51
P	ND	ND	2788	5492	1	1	43	33	42	134
H	ND	ND	1418	19	1	0	265	124	172	228
A	ND	ND	446	911	2	91	358	28	4	2
N	ND	ND	1398	9	8	7	1238	939	6747	768
C	ND	ND	1043	42	10	11	83	42	210	78
B	ND	ND	1512	515	13	60	396	1337	177	116
O	ND	ND	1804	6	39	9	1231	502	483	516
D	ND	ND	2084	247	47	213	1219	2190	1228	405
G	ND	ND	1821	17	ND	7	131	119	165	81
	average		1594	221	13	41			average =	440
	std. dev.		620	349	18	67				509

Data not included in the average is marked in a box.

TABLE 10—Micrograms (μg) of RDX from Detonating Cord, (0.5 cm cut by blade on metal plate).

Person	Bench Begin	Hands Begin	Plate + Blade	Bench End	Hands End	Disposal Vial	Vial 1	Vial 2	Vial 3	Vial 4
B	ND	ND	130	ND	25	1.3	5	154	6	621
C	ND	ND	116	52	5	1.3	47	25	53	158
L	ND	ND	143	416	24	0.81	124	38	58	94.2
P	ND	1.7	61	ND	0	ND	19	10	6	19.4
Q	ND	ND	128	502	16	ND	9	272	555	297
F	ND	1.9	114	767	37	ND	72	74	388	47
E	1.08	5.2	137	738	71	ND	69	413	134	288
N	1.56	1.6	171	357	15	0.85	178	896	598	259
G	ND	2.3	108	85	2	ND	10	105	55	17
M	2.03	178	167	422	21	ND	53	56	335	327
	average		127	417	22	1			average =	174
	std. dev.		31	262	21	0				207

Data not included in the average is marked in a box.

TABLE 11—Micrograms (µg) of PETN Sheet (2 mm wide, cut by blade on metal sheet).

Person	Bench Begin	Hands Begin	Plate + Blade	Surf Bench	Hands End	Disposal Vial	Vial 1	Vial 2	Vial 3	Vial 4
G	ND	ND	13	ND	3.5	0.8	ND	ND	0.70	ND
E	ND	ND	52	ND	2.2	0.5	ND	ND	ND	ND
D	ND	ND	22	ND	ND	2.1	ND	ND	ND	ND
L	ND	ND	115	ND	0.2	ND	ND	ND	ND	ND
A	ND	ND	61	ND	0.4	1.0	ND	ND	ND	ND
B	ND	ND	27	ND	3.5	0.9	1.0	1.2	5.1	1.1
F	ND	ND	57	ND	17.9	14.6	1.9	1.6	0.7	0.6
P	ND	ND	34	ND	0.9	0.3	ND	ND	ND	ND
N	ND	ND	22	ND	0.4	ND	ND	ND	ND	ND
Q	ND	ND	1	ND	ND	14.0	ND	ND	ND	ND
	average		40	0	4	4			average =	2
	std. dev.		33	0	6	6				1

TABLE 12—Micrograms (µg) of residual AN, white powder, by filter paper.

Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
F	ND	ND	16724	4769	1534	87	5359	1089	940	562
A	ND	ND	19	21	232	46	1263	1249	1177	1864
E	ND	ND	19	18	214	8	683	268	2530	359
L	ND	ND	291	38	461	11	2730	2714	3271	3237
D	ND	ND	632	26	453	86	2878	2954	8897	4352
M	ND	ND	10044	1251	270	5	861	2095	225	472
S	ND	ND	34	495	4480	91	8530	10474	9285	8876
B	ND	ND	250	656	98	6	819	636	1367	3658
P	ND	ND	14	125	787	19	4213	9710	8401	10257
N	ND	ND	34512	19	418	8	12224	10233	16412	5583
	average		6254	742	895	37			average =	4318
	std. dev.		11456	1472	1325	37				4124

TABLE 13—Micrograms (µg) of residual TNT Flakes, by filter paper.

Person	Bench Begin	Hands Begin	Al Foil	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
B	ND	ND	35	5.2	1.0	5.8	96	94	107	103
S	ND	ND	77	42	4.7	3.9	104	115	118	101
P	ND	ND	19	0.6	2.2	3.1	100	96	108	108
N	ND	ND	38	1.3	7.4	0.9	119	109	102	105
D	ND	ND	14	2.1	0.8	6.6	116	103	101	90
F	ND	ND	31	30	1.2	1.0	96	95	112	99
A	ND	ND	5	2.4	1.0	1.6	71	90	75	80
M	ND	ND	52	6.3	0.2	0.9	104	81	84	90
L	ND	ND	32	14	1.5	4.2	114	113	116	116
E	ND	ND	70	238	1.3	1.1	104	98	105	112
	average		34	12	2	3			average =	101
	std. dev.		22	15	2	2				12

Data not included in the average is marked in a box.

TABLE 14—Micrograms (µg) of residual C4, by filter paper.

Person	Bench Begin	Hands Begin	Plate + Blade	Bench End	Hands End	Stock Vial	Vial 1	Vial 2	Vial 3	Vial 4
P	ND	ND	96	ND	ND	ND	ND	ND	ND	ND
D	ND	ND	234	ND	ND	7.05	ND	ND	ND	ND
F	ND	ND	13	ND	ND	ND	ND	ND	ND	ND
E	ND	ND	96	ND	ND	ND	ND	ND	ND	ND
L	ND	ND	16	ND	ND	ND	ND	ND	ND	ND
A	ND	ND	29	ND	ND	ND	ND	ND	ND	ND
L2	ND	ND	5	ND	ND	ND	ND	ND	ND	ND
S	ND	ND	247	ND	ND	ND	ND	ND	ND	ND
A2	ND	ND	382	ND	ND	ND	ND	ND	ND	ND
B	ND	ND	30	ND	ND	ND	ND	ND	ND	ND
	average		115	0	0	0			average =	0
	std. dev.		129	0	0	0				0