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Executive Summary of Phase I Demonstrations

Detonation of Conventional Weapons: 155-mm High-Explosive M107 Projectiles

July 1998

**Prepared for
Defense Ammunition Center**

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Abstract

Four experiments were executed from December 1996 through March 1997 within X-tunnel—the contained underground facility at the Department of Energy’s Nevada Test Site (NTS). These are the first large-scale detonation experiments performed in a contained environment with sampling of the effluents.

These experiments, conducted under the direction of the U.S. Army Defense Ammunition Center in Savanna, Illinois, determined the detonation products from 155-mm, high-explosive (HE) M107 projectiles, destroying 6, 24, 24, and 60 projectiles, respectively. These tests were the first phase of a series designed to examine the environmental effects of open burn/open detonation (OB/OD). The tests included performing continuous sampling with online analysis of chamber gas and discrete sampling with offline analysis of bulk gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), metals, and particulates. In addition to these routine measurements, the application of a tunable diode laser (TDL) for measuring bulk gases and a real-time particle analysis instrument was demonstrated in the underground chamber. A series of three rocket motor burn experiments immediately followed these experiments (see the companion to this report, “Executive Summary of Phase II Demonstrations: The Low-Pressure Rocket Motor Burns in X-Tunnel”).

As the first in a series, the data presented here should be considered preliminary. However, several tentative conclusions may be drawn from these detonation experiments: (1) The emissions of the Environmental Protection Agency (EPA) regulated materials were found only in trace levels. (2) In general, metals detected in the residue and particulate samples were dominated by metals already present in the chamber and concrete. (3) There were no releases of metals that exceeded current regulatory limits.

Background Information

The Defense Ammunition Center directed establishment of the Joint Demilitarization Demonstration Technology Program (JDTP) to develop safe, efficient, environmentally acceptable demilitarization processes for the resource recovery and recycling or other disposition of conventional ammunition, rocket motors, and energetics. Strategic and tactical conventional weapons systems whether excess, obsolete, or unserviceable; currently fielded; or being developed for future applications all require disposition planning and capability. The Defense Ammunition Center in Savanna, Illinois directed the studies described here and will submit the final report to Congress.

On August 14, 1996, the Under Secretary of Defense (Acquisition and Technology) sent to Congress a plan for the JDTP in accordance with the Conference Report accompanying the Fiscal Year (FY) 1996 National Defense Authorization Act and page 218 of the House National Security Committee report accompanying the FY 1997 National Defense Authorization Act. Following the Committee recommendation, the program plan was developed using an integrated management structure following the model of the Large Rocket Motor Disposal Program. Thereafter, section 227 of the National Defense Authorization Act for FY 1997 (Public Law 104–201) required the Secretary of Defense to establish an integrated program for the development and demonstration of technologies for the demilitarization and disposal of conventional munitions, rockets, and explosives, and to submit to

Congress a report on the plan for the program. The original program plan was submitted by the Secretary of Defense on March 13, 1997 as required by section 227 of the National Defense Authorization Act for FY 1997. The results contained in that report detail the progress made to characterize emissions from the detonation of conventional munitions.

Program Plan

The goals of the Phase I demonstration are as follows:

- Provide data that describes the environmental impact of open detonation operations;
- Maintain efficiency by producing data that may be used to define optimal size and frequency of demilitarization events; and
- Include data on detonation of large quantities of ammunition to support environmental requirements, to improve open detonation techniques, to develop advanced diagnostic equipment, and to assure system integration and technology transfer.

All these goals are aimed at satisfying Congressional issues while using interservice and interagency government, academia, and commercial resources. This report will be useful to facilities conducting demilitarization events and to those who regulate such activities.

These experiments were directed at baseline emissions from current standardized open detonation procedures. Future studies will benchmark other ordnance as well as improved OB/OD procedures. In addition to the baseline activities, the two novel analytical procedures were demonstrated in the tunnel environment—Tunable Diode Laser (TDL) Spectroscopy and the Los Alamos Aerosol Sampling System (LAASS). These procedures were included to provide continuous sampling of the rapidly changing environment shortly after detonation and to evaluate their application to future aboveground experiments.

Facilities

The Nevada Test Site (NTS) was chosen for the demonstration of open detonation due to its vast, remote, and secure facilities occupying approximately 1350 mile² of a 6,500 mile² federally controlled, set-aside area within southern Nevada. The NTS includes extensive test facilities, bunkers, and underground complexes as well as a complete infrastructure capable of supporting numerous activities.

The X-tunnel test chamber is a large room mined out of volcanic ashfall tuff within Little Skull Mountain, near the southwest corner of NTS. The demonstration chamber [11 m high × 15 m wide × 30 m long (35 × 50 × 100 ft)] provides an open volume of approximately 4,650 m³ (164,000 ft³). Figure 1 shows the tunnel complex; Figure 2, the test chamber.

Figure 1. X-tunnel layout.

Figure 2. X-tunnel Test Chamber.

The walls of the test chamber were sealed with fiber-reinforced shotcrete prior to the first test in an effort to reduce the natural permeability of the ashfall tuff. The test chamber was sealed with a containment plug providing access for the ventilation system, sampling ports, the manway access door, and a secondary double door for passage of heavy machinery. The plug was constructed of a 4-cm (1.5-in.) steel plate backed by I-beams, with the cavity side covered with fiber-reinforced shotcrete. The plug was designed to withstand the blast and overpressure from detonation of 1,082 kg (2,385 lb) of 2,4,6-trinitrotoluene (TNT). A concrete pad was poured in the center of the chamber to provide a level surface for moving heavy objects and to act as solid foundation for ground zero.

Conduits were installed around the plug for arming and firing cables, TDL cables, and gas sampling tubing. Following installation, conduits were gas-blocked to render the chamber gas tight. In addition, blank flanges were installed above the double doors and manways to provide access for sampling-port instrumentation.

Two TDL enclosures were installed in the chamber. Specially designed, shock-hardened enclosures protected the optical line-of-sight absorption instruments from blast debris at each measurement location. One in the left invert (floor) was protected from blast and shrapnel by a 2.54-cm (1-in.-) thick, quarter sphere. The other was located 5-m (16-ft) high on the left rib and was protected by a blast mat hung approximately 1.2-m (4-ft) from the TDL box. Each box had a heavy door that was released by explosive cable cutters after the detonation event. The lasers and signal processing electronics were housed in a compact instrumentation rack located in a trailer at the tunnel portal.

Four stainless-steel lines, 0.635-cm (0.25-in.) o.d., were emplaced in the chamber. One terminated in a sampling can on the left rib on the wall about 4.6 m (15 ft) above the floor of the chamber and behind the TDL rib-mounted enclosure; another terminated in a sampling can in the floor just in front of the right side of the concrete pad. These lines exited the chamber in a trench below the sill plate of the barrier and entered a downhole valve-switching box in the tunnel drift. The other two lines passed through the plug access ports, but were not used in this series.

A downhole switch box was located about 8 m (25 ft) from the portal side of the barrier, which contained the manual shut-off valves for each sampling line, a water trap, pressure gauge, and other shut-off valves and features.

Two approximately 213-m- (700-foot-) long stainless-steel 0.635-cm (0.25-in.) o.d. tubes from the downhole switch box connected to the inlet skid. At the inlet skid, one line was chosen for discrete sampling and online analysis. During the detonation experiments, the other sampling line had no flow. Water was removed from the sample gas by a large Drierite filled trap between the inlet and pumping skids. Online analysis of gas composition was done in the Mobile Noble Trailer.

Test Ordnance

The four detonation tests destroyed 155-mm high-explosive (HE) M107 projectiles (hazard class/division 1.1D)(DODAC: 1320-D544), each of which contained 6.98 kg (15.4 lb) of Composition B [63 wt% hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), 36% TNT, 1% wax] and 0.13 kg (0.30 lb) of a supplementary charge (TNT/1.5% barium stearate). As shown in Figure 3, each projectile consisted of a steel body and lifting lug, weighing 34.47 kg (76 lb), and had a 0.608 kg (1.34 lb) copper rotating band and 29 g (0.065 lb) of aluminum parts. Each projectile was coated with 2.39 g of zinc phosphate and 5.64 g of zinc chromate. The munitions were detonated with the lifting lug in place, but without the plastic protector grommet for the rotating band. They were shipped and detonated without the fusing assembly.

Figure 3. Projectile, 155-mm, HE M107 metal parts assembly.

Composition C4¹ explosive was used as the donor charge to initiate the 155-mm projectiles. The C4 was initiated with slip-on boosters, 50 grains/ft primacord, and exploding bridge wire detonators. A gas recovery standard was released in the chamber by explosively opening, at the time of detonation, a compressed-gas cylinder of krypton with a copper linear shaped charge (clsc). On two tests an additional cylinder of helium was also opened in this manner to determine if helium could be used as the recovery standard. Table 1 provides information related to each 155-mm projectile test.

Table 1. 155-mm HE M107 projectile test specifics.

Explosive	Test 1: Banshee	Test 2: Polaris	Test 3: Beast	Test 4: Colossus
Comp "B"	41.9 kg	167.6 kg	167.6 kg	419.0 kg
Supplemental Charge	0.82 kg	3.3 kg	3.3 kg	8.2 kg
C4 (RDX)	6.80 kg	27.2 kg	27.2 kg	38.5 kg
Slip On Boosters (PETN)	0.24 kg	0.48 kg	0.48 kg	0.68 kg
Primacord (PETN)	0.032 kg	0.11 kg	0.11 kg	0.15 kg
Copper Linear Shape Charge (RDX)	0.192 kg	0.192 kg	0.384 kg	0.192 kg
RP1 Detonator (RDX)	1.25 g	1.25 g	2.50 g	1.25 g
RP83 Detonator (RDX)	2.22 g	4.44 g	4.44 g	4.44 g
Total explosives weight	50.0 kg	198.9 kg	199.1 kg	466.8 kg
Total added metal	210.4 kg	842.0 kg	842.0 kg	2106.0 kg
Total added aluminum	0.18 kg	0.71 kg	0.71 kg	1.77 kg
Total added barium	2.4 g	9.1 g	9.1 g	24.0 g
Total added chromium	9.72 g	38.88 g	38.88 g	97.20 g
Total added copper	4.61 kg	15.5 kg	16.5 kg	37.4 kg
Total added zinc	19.5 g	78.0 g	78.0 g	195.0 g

¹ C4: C4 contains 91% RDX, 5.3% di(2-ethylhexyl) sebacate, 2.1% polyisobutylene, and 1.6% motor oil by weight).

(a) Banshee Test

(b) Polaris/Beast Tests

(c) Colossus Test

Figure 4. Projectile layout for all four tests: (a) Banshee, (b) Polaris/Beast, and (c) Colossus.

Overview of Experiments

There were four preliminary tests performed as listed below. Figure 4 shows the projectile layout for all four tests:

- Test 1: Banshee—detonated six projectiles on December 18, 1996.
- Test 2: Polaris—detonated 24 projectiles on January 22, 1997.
- Test 3: Beast—detonated 24 projectiles on February 26, 1997.
- Test 4: Colossus—detonated 60 projectiles on March 19, 1997.

Test 1: Banshee

Banshee had six projectiles aligned side-by-side with the lifting lugs facing the right rib and were placed on a 2.54-cm- (1-in.-) thick steel plate on a concrete pad. A tracer bottle of krypton was placed on a smaller concrete pad, behind the shells, as was done for all four experiments.

The Banshee event ripped a hole in the steel plate and made a small crater in the concrete below. The entire small concrete pad on which the projectiles were laid moved a few inches relative to the larger, adjacent concrete pad. Several large metal fragments struck the containment plug. One of these penetrated about 2 cm (0.75 in.) into the 4-cm- (1.5-in.-) thick metal plate. Several large rips were found in the blast mats which protected the containment plug and instruments. The fiber-reinforced shotcrete on the tunnel back (roof) directly above ground zero was partially separated from the rock behind, and wire mesh was exposed. In some places loose material dangled from the wire mesh. This type of damage is expected since the larger and faster moving shrapnel fragments typically eject radially from the centerline of the projectile.

Prior to this event, we speculated that if the lifting lugs remained in tact, and, if they were accelerated to near the maximum velocity measured during weapon effectiveness tests, they would be capable of severe tunnel damage and penetration of the containment plug. After the Banshee event, we were not able to find any trace of the lifting lugs or tunnel damage that could be attributed to them. Apparently the lugs shattered as the detonation wave passed through them and did not produce large fragments. In all subsequent tests half of the projectiles were oriented with the lugs toward the containment plug, and the other half was oriented directly away from the plug. In addition, an additional layer of fiber-reinforced shotcrete was applied to the chamber side of the plug.

This initial detonation test was also the initial testing of the sampling equipment and sampling approach during a full-scale detonation. Thus, the Banshee test served to debug the sampling equipment and to refine the sampling methodology. The air sample results from Banshee should only be used for qualitative purposes, and not for quantitative purposes. The large amount of water produced in the detonation condensed in the sampling system and clogged filters. Sample lines and filters were heated during subsequent experiments, eliminating this issue. The Banshee air results are, in general, not presented in various tables and figures throughout this summary report but are included in the individual reports that accompany this summary.

Test 2: Polaris

Polaris had 24 projectiles placed in two rows of 12 with the lifting lugs oriented outward, with one row pointed directly at the containment plug. The 24 projectiles were placed on a 2.54-cm- (1-in.-) thick mild steel plate, which was placed over the crater excavated during Banshee. There was considerable damage to the concrete pad and a large hole was removed from the steel plate. We observed damage to the tunnel back that appeared to be about three times that seen in Banshee, even though no hanging debris were visible. The containment plug and blast mats experienced no significant shrapnel damage.

Test 3: Beast

The orientation of the 24 projectiles was the same as Polaris; but, instead of using the steel plate for placement, the crater excavated during the previous test was filled in with gravel, and the projectiles were placed on top of this gravel bed. The major difference between Polaris and Beast was the substrate directly under the shells and the distance of the projectiles: for Beast, they were positioned 2.4 m (8 ft) farther away from the containment plug than for Polaris. The Beast event left a crater approximately 3-m wide $\times$ 1.4-m deep (9 $\times$ 4.5-ft) with gravel evenly dispersed throughout the chamber and large pieces of shrapnel also found throughout the chamber. Damage to the blast mats, barrier, and experiments was not noticeable. The video camera observing the outside of the containment plug recorded a small puff of dust and gas escaping from around the double doors.

Test 4: Colossus

The 60 projectiles in Colossus were stacked in two rows, two projectiles deep. The lifting lugs were oriented outward from the stack with one row pointed directly at the containment plug, and the other at the tunnel face. The crater from the previous test was again filled in with gravel and the projectiles were placed on top of the gravel bed. The C4 initiation explosive was attached to exposed projectile in this stack.

The Colossus event created a crater 4.6 $\times$ 6.0 m wide $\times$ 1.5 m deep (15 $\times$ 20 $\times$ 5 ft). There was more damage to the tunnel back above ground zero than in any of the previous events. There was also evidence of some leaking of the chamber gas through the conduits and into the main tunnel drift.

Pressure and Temperature Measurements

To take various pressure and temperature measurements during the experiments, 14 thermocouples were placed throughout the test chamber and the data were recorded by computer. To protect the thermocouples from damage from prompt pressure and shrapnel, they were placed in hardened enclosures or behind the TDL support structure on the rib. The thermocouple within the rib TDL box delivered readings that were most representative of the chamber gases because the TDL enclosure protected the thermocouple but later allowed contact with chamber gas after the box opened. These data were used to construct Figure 5. Other thermocouples were protected from blast and shrapnel

damage and were more thermally insulated from the chamber gas. Please note that these thermocouples do not measure well the early-time (non-equilibrium) temperature distributions. In particular, the experiment with the largest net explosive weight (NEW) produced the highest peak temperature; Polaris and Beast used the same NEW and produced significantly different peak temperatures.

Figure 5. Chamber gas temperature.

Both equilibrium and prompt pressure were measured at the chamber plug. Figure 6 presents the equilibrium pressure data. The rapid decrease in pressure is mainly due to cooling and not to chamber gas leakage. The event with the largest NEW produced the highest peak equilibrium pressure, and significant differences were found between the two 24 projectile experiments (Beast and Polaris).

Figure 6. Equilibrium pressure measurements.

The prompt pressure from these experiments was measured to evaluate the stress that the containment plug would experience. Figure 7(d) shows the measured prompt pressure for the largest (Colossus) experiment at a maximum pressure of 250 psig, which conforms well to the maximum calculated pressure of 240 psig. The 240 psig maximum expected prompt pressure was the basis of the design criteria minimum safety factor of 2.5 for the containment plug. As shown, there was a small difference in prompt pressure between the two 24 projectile experiments (Beast and Polaris), with Polaris showing the higher pressure.

Figure 7. Prompt pressure measurements.

Bulk Gas Analysis

Bulk gas measurements were obtained by drawing samples continuously through stainless-steel lines from the test chamber to a trailer outside the tunnel, which contained real-time analytic instrumentation and apparatus for collecting grab samples. There were two inlets to the gas sampling system within the test chamber: one on the invert (floor), near the right rib near the concrete pad; and another on the left rib, on the TDL support structure, about 4.6 m (15 ft) above the invert. One of these lines could be sampled at any one time. Instrumentation in the trailer consisted of a portable gas chromatograph;² a mass spectrometer;³ two continuous emission monitors⁴ for carbon dioxide, carbon monoxide, oxygen, and nitrogen dioxide using a combination of infrared and electrochemical cells; and two infrared⁵ sensor units for nitric oxide and carbon monoxide.

Figure 8 shows typical data for these experiments (actual data from Polaris). Acidic gases such as carbon dioxide and nitric oxide show maxima shortly after detonation and slowly decrease in concentration thereafter. Gases such as krypton, oxygen, and carbon monoxide exhibit changes in concentration due to the detonation and remain at a constant volume (mole) fraction of the chamber gases until the chamber purge system is engaged. It is likely and expected that the acidic gases would react with calcium oxide in the fiber-reinforced shotcrete to form carbonates, nitrates, nitrites, etc. Thus carbon dioxide is scrubbed from the chamber and the concentration of carbon dioxide is found to slowly decrease throughout the measurement period.

Prior to the detonation experiments, we performed a mix test in which cylinders of carbon dioxide, krypton, and helium were each explosively opened with a linear shaped charge and the concentration of materials in the chamber was monitored. This experiment served as a fully instrumented dry run test, and allowed us to determine the dynamics of chamber gas concentrations and to remeasure the tunnel volume. All instruments performed well during this low dust, low water vapor test.

Table 2 shows calculated tunnel volumes from the mix test. The tunnel volume derived from the release of helium did not agree with the other two tracers and with the measured tunnel volume. This is perhaps due to the high permeability of helium in the porous tunnel walls and floor and resulted in a higher than expected tunnel volume due to selective loss from the chamber. Tunnel volume calculated from the peak carbon dioxide concentration, the krypton concentration, and the measured chamber volume agreed quite well. The volume calculation using a linear fit-to-time-zero carbon dioxide concentration was about 6% too high; this was the first time a large amount of carbon dioxide was released in the chamber, so the initial absorption with the walls may have been non-linear.

² Gas chromatograph: Model M100, MTI Analytical Instruments.

³ Mass spectrometer: Leybold Quadrupole H200M.

⁴ Emission monitors: Geotechnical Instruments Ltd. Anagas model CD1.4.

⁵ Infrared sensor units: Horiba 510 series.

Figure 8. Gas concentrations from Polaris by continuous monitoring (curves), grab samples (symbols), carbon dioxide (solid line and squares), and oxygen (dashed line and diamonds).

Table 2. Mix test tracer data and chamber volume results.*

Method	Tracer chamber vol [m ³ (ft ³)]	Uncertainty (±) [m ³ (ft ³)]
Helium	5,423 (191,500)	272 (9,600)
Fit to tzero carbon dioxide	4,900 (173,000)	227 (8,000)
Peak carbon dioxide	4,616 (163,000)	227 (8,000)
Krypton	4,616 (163,000)	184 (6,500)
Laser survey chamber volume	4,650 (164,000)	—

*Ideal gas law chamber volume.

Prior to these experiments, we calculated the expected gas concentrations, making the assumption that all of the carbon oxidized to carbon dioxide. Table 3 presents the results of these calculations and measurements from each test. These values were determined by extrapolation of measured data back to time zero. The results are very close to the calculated values based on explosives inventory and expected complete combustion. As shown in Table 3, the carbon dioxide concentration is lower than expected, indicating that incomplete combustion occurred.

Table 3. Major and minor gas concentrations in X-tunnel at detonation time of 155-mm HE M107 projectiles.¹

Tests	Nitrogen	Oxygen	Carbon Dioxide	Argon	Krypton ²	Helium
Chamber Air Preshot (vol%)	78.10	20.95	0.02	0.93	0.00	0.00
Mixtest						
Calculated vol%	77.53	20.80	0.27	0.93	0.25	0.23
Measured vol%	77.5	20.9	0.27	0.88	0.24	0.19
± Measured vol% ³	0.5	0.5	0.01	0.02	0.01	0.01
Banshee						
Calculated vol%	77.82	20.39	0.62	0.93	0.24	0.00
Measured vol%	77.32	20.99	0.50	0.90	0.24	0.02
± Measured vol%	0.20	0.05	0.02	0.01	0.01	0.01
Polaris						
Calculated vol%	77.58	18.90	2.37	0.91	0.24	0.00
Measured vol%	77.66	18.97	2.07	0.90	0.245	—
± Measured vol%	0.10	0.10	0.05	0.01	0.008	—
Beast						
Calculated vol%	77.41	18.85	2.36	0.91	0.24	0.22
Measured vol%	77.71	18.91	1.90	0.88	0.23	0.122
± Measured vol%	0.50	0.06	0.03	0.01	0.01	0.002
Colossus						
Calculated vol%	77.16	16.31	5.40	0.89	0.23	0.00
Measured vol%	77.83	16.23	4.31	0.85	0.22	—
± Measured vol%	0.50	0.06	0.10	0.01	0.01	—

¹Conditions used for calculated vol%: Temp, 20°C; Relative Humidity, 60%; explosives' products mixed in 164,000 ft³ of air; 200 ppmv CO₂ initial; assumes only CO₂, N₂, H₂O, and BaO are formed as products. H₂O and BaO are not included in the gas composition (data reported on a "dry gas" basis).

²The amount of Kr tracer for each test was 34,700g (76.6 lb).

³Uncertainties are 1 σ .

Table 4 presents the trace gas compositions determined for the mix test and each 155-mm projectile open detonation experiment. Carbon monoxide, hydrogen, nitrous oxide, methane, and some other incomplete combustion products are also present. If the combustion process went to completion the concentration of materials presented in Table 4 should be zero. These values give a good measure of the completeness of combustion.

Table 4. Trace gas concentrations in the chamber at detonation time of 155-mm HE M107 projectiles.

Test	Carbon Monoxide	Hydrogen	Nitric Oxide	Methane
Mixtest				
ppmv	15	NM	NR	NM
± ppmv	2	—	—	—
Banshee				
ppmv	150	50	NR	<10
± ppmv	30	10	—	—
Polaris				
ppmv	1158	349	56	50
± ppmv	60	10	3	10
Beast				
ppmv	1731	540	50	70
± ppmv	60	20	3	10
Colossus				
ppmv	4117	1412	90	90
± ppmv	100	20	5	10

ND=not detected, NR=not reported, NM=not measured. Uncertainties are 1 σ .

Table 5 presents the summary of the carbon balance for these experiments. The three major carbon-containing gases account for the 86 to 93% of the carbon. A small fraction of this carbon is in the trace levels of volatile organic and semi volatile organic (VOC/SVOC) compounds measured in these tests. The difference between the measured and expected values could be due to formation of carbon (soot) during these tests that was not measured, or a systematic error in calculating carbon dioxide concentrations.

Table 5. Carbon balance.¹

Test	Carbon Dioxide	Carbon Monoxide	Methane	Gas sum
Mixtest				
peak carbon dioxide	99.44	0.56	—	100.0
Banshee				
% Total carbon	83.18	2.56	<0.17	85.74
±% Total carbon	4.78	0.52	—	4.81
Polaris				
% Total carbon	85.64	4.86	0.21	90.71
±% Total carbon	3.48	0.30	0.04	3.51
Beast				
% Total carbon	83.87	7.72	0.31	91.90
±% Total carbon	3.88	0.43	0.05	3.92
Colossus				
% Total carbon	84.88	8.14	0.18	93.20
±% Total carbon	4.33	0.42	0.02	4.35

¹% (carbon amount in gas due to explosive)/(initial explosive carbon amount).

Uncertainties are 1 σ . Upper limit values are not included in the sum.

Organic Chemical Emissions

Samples for determination of VOCs were collected in passivated stainless-steel canisters and later analyzed by EPA Compendium Method Technical Order 14 (TO) and TO-12. Table 6 presents VOCs that were detected at concentrations >10 ppbv.

Table 6. Selected VOC emissions for detonation of M107 projectiles.

VOC	Concentration, ppbv			
	Polaris	Beast	Colossus	Average
Average Concentration >1,000 ppbv				
Total Nonmethane Hydrocarbons	4590	5930	11500	7340
Ethylene	3480	ND	ND	3480
Acetaldehyde	4790	1350	2860	3000
Acetylene	2200	ND	ND	2200
Methylene chloride	205	3320	1680	1735
Propylene	1130	906	1510	1182
1-Butene	1020	654	1490	1055
Average Concentration >100, but <1000 ppbv				
Benzene	1110	530	1310	983
Acetonitrile	731	769	471	657
Ethane	648	ND	ND	648
Acetone	892	285	491	556
Benzaldehyde	638	56	299	331
1-Butanol	588	162	162	304
trans-2-Butene	175	107	255	179
cis-2-Butene	148	99	247	165
Toluene	192	110	176	159
Styrene	228	15	183	142
Butyraldehyde	166	77	183	142
Propane	154	106	80	113
Halocarbon 134A	61	248	2	104
Average Concentration <100 ppbv				
Chlorodifluoromethane	18	49	213	93
Acrylonitrile	78	38	80	66
Ethanol	65	66	32	55
Butyl acrylate	94	8	35	46
n-Butane	49	35	49	44
1-Pentene	40	36	46	41
Naphthalene	67	ND	13	40
1-Propanol	28	ND	46	37
Chloromethane	45	32	30	36
2-Butanone	54	16	35	35
Isobutane	73	9	11	31
1-Hexene	28	31	33	31
Ethylbenzene	39	19	27	28
m/p-Xylene	48	12	21	27
Hexanal	27	ND	14	20
1-Heptene	24	14	17	18
Isoheptane	24	2	ND	13
Vinyl acetate	11	11	15	12
1,3-Butadiene	12	7	16	12
trans-2-Pentene	11	9	14	11
3-Methyl-1-butene	12	8	12	11
Neohexane	ND	ND	10	10
n-Pentane	8	10	13	10
Cyclopentene	7	10	13	10
2-Propanol	13	ND	7	10
o-Xylene	13	5	8	9
4-Methyl-1-pentene	7	ND	10	8
Isohexane	5	11	7	7
1-Decene	13	3	6	7

Note: Only compounds found in concentrations >10 ppbv are included in Table 6. ND=not detected.

A sampling system modeled after EPA SW-846 Method 0010 was used to collect samples for determination of SVOCs. The recovered samples were later analyzed by EPA SW-846 Method 8270. Table 7 presents emission factors for SVOCs that were detected at levels >10 µg in the sample.

Table 7. Selected SVOC air emissions.

SVOC	Concentration, µg/m ³			
	Polaris	Beast	Colossus	Average
Acetophenone	6.70×10^{-3}	1.87×10^{-2}	4.44×10^{-2}	2.33×10^{-2}
Benzoic acid	3.22×10^{-2}	1.89×10^{-2}	2.35×10^{-2}	2.49×10^{-2}
Benzyl alcohol	1.02×10^{-3}	2.81×10^{-3}	5.50×10^{-3}	3.11×10^{-3}
2-Methylnaphthalene	4.62×10^{-3}	2.08×10^{-2}	2.18×10^{-2}	1.57×10^{-2}
Naphthalene	1.72×10^{-2}	3.57×10^{-2}	1.12×10^{-1}	5.50×10^{-2}
Nitrobenzene	1.34×10^{-3}	3.28×10^{-3}	5.62×10^{-3}	3.41×10^{-3}
2-Nitrophenol	1.13×10^{-3}	3.98×10^{-3}	1.62×10^{-2}	7.10×10^{-3}

Note: Only compounds found at levels >10 µg in the sample are included in Table 7.
Units are µg compound/m³ of chamber gas sampled.

In general, emissions of VOCs were very low with the vast majority showing concentrations of <1 ppmv. Only 6 individual compounds could be detected in amounts that exceeded 1 ppmv, and none exceeded 4 ppmv.

Residue samples from the NTS series were analyzed for energetic materials and SVOCs (SW-846 Method 8330, proposed Method 8320, and Method 8270). In the first test, Banshee, a residue of 41 ppb of RDX was measured and no energetic materials were detected from the remaining NTS experiments. As shown in Table 8, very low levels of SVOCs were observed. The concentration of many of the SVOCs identified decreased as the NEW of the test increased. Most of the SVOCs identified showed concentrations of <100 µg/kg, and only two compounds showed concentrations of >1000 µg/kg.

Table 8. SVOCs in residue samples.

SVOC	Concentration in Residue Samples, $\mu\text{g/kg}$			
	Banshee	Polaris	Beast	Colossus
Acenaphthylene	26	ND	8	ND
Acenaphthene	ND	11	ND	ND
Anthracene	13	ND	ND	ND
Benzo(a)anthracene	20	ND	ND	ND
Benzo(b)fluoranthene	21	ND	ND	ND
Chrysene	33	ND	ND	ND
Dibenzofuran	15	38	ND	9
Fluoranthene	59	44	13	7
2-Methylnaphthalene	1105	1424	107	60
Naphthalene	49	188	22	55
Phenanthrene	151	143	39	31
Pyrene	40	23	11	6
2,4,5-Trichlorophenol	ND	ND	ND	83

ND = not detected (detection limits are compound specific and range between 5 and 40 $\mu\text{g/kg}$).

Metal Analysis

Metals were measured in numerous positions throughout these experiments due to their persistence in the environment and prominence in environmental regulations (Resource Conservation and Recovery Act). Total suspended particulate filters (40 CFR 50, Appendix B), vapor phase samples (EPA Method 29), chamber residue (SW-846 Method 1311, 6010, and 7470), coupons hung in the chamber to collect dust, material collected by the LAASS, and various chamber materials were analyzed for a suite of regulated and non-regulated metals. Table 9 presents metals found in total suspended particulates (TSP) sample filters; Table 10 provides a summary of airborne metals; and Table 11 shows the concentration of metals in the residue samples and in background materials.

Table 9. Metals analysis of TSP filters.

Metal	TSP Filter Concentrations (mg/kg)			
	Banshee	Polaris	Beast	Colossus
Aluminum	32,900	23,400	36,667	39,500
Antimony	25	ND	ND	11
Arsenic	17	17	ND	10
Barium	475	448	593	699
Beryllium	1	1	1	2
Cadmium	3	4	3	3
Calcium	169,000	144,000	143,667	106,500
Chromium	79	85	72	86
Cobalt	11	6	10	15
Copper	2,310	1,920	1,427	1,900
Iron	55,400	54,100	40,267	54,200
Lead	64	68	67	40
Magnesium	6,870	6,240	6,363	5,330
Manganese	606	594	529	692
Mercury	1	1	2	1
Molybdenum	37	35	29	62
Nickel	53	54	90	70
Phosphorus	NR	NR	652	798
Potassium	12,300	13,000	13,933	17,400
Selenium	7	ND	ND	2
Silver	ND	2	3	3
Sodium	8,900	8,170	6,963	7,450
Strontium	445	380	391	348
Thallium	13	14	26	30
Titanium	2,410	6,560	3,883	4,390
Vanadium	31	33	39	52
Zinc	622	824	557	1,042

ND=not detected, NR=not reported.

Table 10. Particulate matter, metal, and hydrogen cyanide air emissions.

Compound	Polaris	Concentration, mg/m ³		
		Beast	Colossus	Average
Particulates				
PM ₁₀	4.32 × 10	9.56 × 10	1.02 × 10 ⁺²	8.03 × 10
TSP	2.25 × 10 ⁺²	2.97 × 10 ⁺²	8.37 × 10 ⁺²	4.53 × 10 ⁺²
HCN	1.23 × 10 ⁻¹	7.95 × 10	3.04 × 10 ⁻¹	2.79
Metals				
Average Concentration >10				
Aluminum	5.26	1.09 × 10	3.30 × 10	1.64 × 10
Calcium	3.24 × 10	4.26 × 10	8.91 × 10	5.47 × 10
Iron	1.22 × 10	1.20 × 10	4.53 × 10	2.32 × 10
Average Concentrations >1.0, but <10				
Magnesium	1.40	1.89	4.46	2.58
Potassium	2.92	4.14	1.46 × 10	7.22
Sodium	1.84	2.07	6.23	3.38
Titanium	1.48	1.15	3.67	2.10
Average Concentrations >1.0 × 10 ⁻¹ , but <1.0				
Barium	1.01 × 10 ⁻¹	1.76 × 10 ⁻¹	5.85 × 10 ⁻¹	2.87 × 10 ⁻¹
Copper	4.32 × 10 ⁻¹	4.24 × 10 ⁻¹	1.59	8.15 × 10 ⁻¹
Manganese	1.34 × 10 ⁻¹	1.57 × 10 ⁻¹	5.78 × 10 ⁻¹	2.90 × 10 ⁻¹
Phosphorus	NR	1.93 × 10 ⁻¹	6.68 × 10 ⁻¹	4.31 × 10 ⁻¹
Strontium	8.55 × 10 ⁻²	1.16 × 10 ⁻¹	2.91 × 10 ⁻¹	1.64 × 10 ⁻¹
Zinc	1.85 × 10 ⁻¹	1.65 × 10 ⁻¹	8.72 × 10 ⁻¹	4.07 × 10 ⁻¹
Average Concentrations >1.0 × 10 ⁻² , but <1.0 × 10 ⁻¹				
Chromium	1.91 × 10 ⁻²	2.15 × 10 ⁻²	7.22 × 10 ⁻²	3.76 × 10 ⁻²
Lead	1.53 × 10 ⁻²	1.98 × 10 ⁻²	3.36 × 10 ⁻²	2.29 × 10 ⁻²
Molybdenum	7.78 × 10 ⁻³	8.63 × 10 ⁻³	5.22 × 10 ⁻²	2.29 × 10 ⁻²
Nickel	1.21 × 10 ⁻²	2.67 × 10 ⁻²	5.84 × 10 ⁻²	3.24 × 10 ⁻²
Thallium	3.24 × 10 ⁻³	7.58 × 10 ⁻³	2.51 × 10 ⁻²	1.20 × 10 ⁻²
Vanadium	7.44 × 10 ⁻³	1.16 × 10 ⁻²	4.38 × 10 ⁻²	2.09 × 10 ⁻²
Average Concentrations >1.0 × 10 ⁻³ , but <1.0 × 10 ⁻²				
Antimony	ND	ND	9.54 × 10 ⁻³	9.54 × 10 ⁻³
Arsenic	3.89 × 10 ⁻³	ND	8.07 × 10 ⁻³	5.98 × 10 ⁻³
Beryllium	2.59 × 10 ⁻⁴	3.78 × 10 ⁻⁴	2.05 × 10 ⁻³	8.96 × 10 ⁻⁴
Cadmium	9.13 × 10 ⁻⁴	9.57 × 10 ⁻⁴	2.91 × 10 ⁻³	1.59 × 10 ⁻³
Cobalt	1.35 × 10 ⁻³	2.95 × 10 ⁻³	1.26 × 10 ⁻²	5.63 × 10 ⁻³
Mercury	1.20 × 10 ⁻⁴	8.72 × 10 ⁻³	1.65 × 10 ⁻²	8.45 × 10 ⁻³
Selenium	ND	ND	2.07 × 10 ⁻³	2.07 × 10 ⁻³
Silver	4.90 × 10 ⁻⁴	7.82 × 10 ⁻⁴	2.80 × 10 ⁻³	1.36 × 10 ⁻³

ND=not detected, NR=not reported.

The vast majority of the metals measured are derived from the chamber materials and not from the projectiles or other experimental materials. The following metals were found at levels higher than those in the chamber (background) materials: aluminum, chromium, copper, iron, nickel, potassium, sodium, thallium, titanium, and zinc.

Iron and copper in the various samples are derived from the projectiles and experimental materials. A relatively small fraction of the copper could be accounted for in the TSP fraction. For example, 0.01% of the copper that was present in the projectiles and experimental materials ended up as suspended particulate matter during Colossus. The vast majority of the copper measured was from the projectile and not the clsc, and these copper recovery values were not corrected for the contribution of chamber materials. TSP filters collected more iron in the Polaris event than in the Beast event. This difference is possibly due to the added iron from the steel plate on which the 155-mm projectiles were placed prior to the Polaris event. The concentration of iron was higher in the TSP filters than in background materials. This iron is clearly derived from the metal parts assembly of the projectiles.

Table 11. Metals in the residue samples and in background materials.

Metal	Concentration (mg/kg)								
	Banshee	Polaris	Beast	Colossus	Concrete	Shotcrete	Rock	Aggregate	Soil
Aluminum	9,895	11,000	NR	NR	8,290	9,170	7,800	NR	NR
Antimony	0.9	ND	ND	ND	ND	ND	ND	ND	ND
Arsenic	9.6	10.7	4.8	5.7	9	11.2	2.03	1.38	3-6
Barium	NR	252	280	324	148	90.9	451	942	302-454
Beryllium	ND	ND	0.2	ND	ND	ND	ND	0.193	ND-0.4
Cadmium	0.8	0.7	0.4	0.2	0.4	0.189	ND	ND	0.2-0.3
Calcium	NR	NR	NR	NR	126,700	193,000	5,600	—	NR
Chromium	23.2	26.6	11.0	14.3	28	12.6	4.53	1.80	11-13
Cobalt	NR	NR	3.2	3.9	4	4.37	6.12	1.59	4-5
Copper	1,855	NR	NR	NR	36	20.1	4.87	NR	NR
Iron	NR	NR	NR	NR	11,000	9410	10700	—	NR
Lead	16.3	13.2	7.0	7.5	7	12.9	5.48	7.55	9-15
Magnesium	NR	NR	NR	NR	3,280	8160	4640	—	NR
Manganese	NR	NR	304	237	205	134	257	264	217-235
Mercury	ND	ND	ND	ND	NR	NR	NR	ND	ND
Molybdenum	NR	NR	NR	NR	2	2.29	ND	—	NR
Nickel	16.1	18.9	8.1	12.4	14	8.03	3.03	2.79	6-10
Phosphorus	NR	NR	495	584	461	353	904	85.2	670-677
Potassium	NR	NR	NR	NR	2,405	2,180	4,770	—	NR
Selenium	1.0	1.3	0.7	1.0	ND	ND	ND	ND	1
Silver	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sodium	NR	NR	NR	NR	556	263	1530	NR	NR
Strontium	NR	NR	NR	NR	382	323	55.5	NR	NR
Thallium	NR	NR	NR	ND	1	ND	1.14	ND	ND
Titanium	NR	NR	NR	NR	273	348	698	NR	NR
Vanadium	NR	NR	NR	NR	22	17.8	20.4	NR	NR
Zinc	94	113	46	64	36	39.9	22.9	27.6	39-56

ND=not detected, NR=not reported.

The concentration of aluminum, nickel, sodium, thallium, and titanium in the TSP samples are all higher than in samples of background materials. Even though there is 0.025 lb of aluminum alloy per projectile, there does not appear to be a significant source of these metals in the experimental materials when compared with the levels of metals found in the TSP samples and in chamber residues. Either there is a selective enrichment of these metals in the suspended fraction or there is a source that is yet to be identified. The selective enrichment of aluminum is the best explanation since the aluminum was only found in elevated concentrations in the TSP samples and not in the residue samples.

Chromium and zinc were found in concentrations in the TSP and residue samples that exceeded those found in the background materials. Both of these metals are present in the projectiles. Although barium is present in the supplementary charge, the amounts present are too low to add significantly to the high concentrations found in the chamber materials. None of the concentration of metals exceeded the Toxicity Characteristic Leaching Procedure (TCLP) regulatory limit as shown in Table 12.

Table 12. TCLP metals analysis of residue samples.

Metal	Concentration (mg/L)				Regulatory Level, mg/L
	Banshee	Polaris	Beast	Colossus	
Arsenic	ND	0.0055	0.0115	0.012	5
Barium	0.757	0.817	0.643	0.630	100
Cadmium	ND	ND	ND	ND	1
Chromium	0.124	0.12	0.0075	0.012	5
Lead	ND	ND	ND	ND	5
Mercury	ND	0.0006	ND	ND	0.2
Selenium	ND	ND	ND	ND	1
Silver	ND	ND	ND	ND	5

ND=not detected.

In addition to the above analyses, metal coupons were hung in the chamber in the blast mat that protected the containment plug. Dust that collected on these coupons was washed off and analyzed for metals by mass spectrometry at the University of Nevada, Las Vegas (UNLV). Their final report may be obtained from Sandia National Laboratories (SNL), but due to the non-standard collection method no conclusions are presented here.

Tunable Diode Laser Measurements

The goal was to use the tunable diode laser (TDL) instrumentation to obtain time-resolved analyses of reactive, hazardous gases as they evolved from multiple experimental positions in the X-tunnel test chamber. The temporal evolution of these species at the different emplacements provides an indication of completeness of combustion and mixing. One gas species of interest is hydrogen cyanide since it is very difficult to measure reliably with conventional techniques. During the test series, measurements of carbon monoxide, carbon dioxide, and water were also performed. For these experiments, optical line-of-sight absorption measurements were made at two different locations in the X-tunnel test chamber—the rib and invert. Specially designed, shock-hardened enclosures were protected from blast debris at each measurement location. The lasers and signal processing electronics were housed in a compact instrument outside the tunnel. From a mechanical standpoint the TDL equipment performed quite well. During severe ground motion and blast loading, no misalignment of optics, mechanical failures, or shrapnel damage were evident.

A commercial gas monitor, based on TDL spectroscopy, was substantially modified by SNL, for dual-species, spectroscopic measurements, and was the foundation for these in-situ experiments. This technique detects molecular species using optical absorption by vibrational transitions in overtone and combination modes at wavelengths near 1.30 and 1.55 μm in the near-infrared portion of the electromagnetic spectrum. Near-infrared distributed-feedback diode-lasers emit extremely narrow, single-mode radiation that can be tuned continuously (i.e., without mode hops) across molecular absorption lines by varying injection current or device temperature near room temperature. The sensitivity of the near-infrared TDL method to molecular species is greatly enhanced by high-frequency modulation of the laser beam and phase-sensitive detection.

Laser light was transported to the test chamber and diagnostics enclosures via hardened fiber optics. DC power was supplied to sensitive photodetectors in the enclosures using shielded twisted conductors, and electrical signals from these detectors were returned from the test chamber by coaxial cable to the data acquisition computer located in a trailer near the tunnel entrance. The sampling rate of the instrument was nominally 1-hz, and measurements of gas species concentrations began roughly 3 sec before time zero.

Figure 9 shows the laser transmittance from the rib emplacement. The Beast experiment showed transmittance to 50% with the remaining tests ranging between 70 and 85%. The transmittance was considerably lower in the invert emplacement, mainly due to large amounts of dust and debris that settled within the invert enclosure, which was not surprising since those windows were in a direct line of sight with falling dust and particulates. The laser transmittance reflects the combined influence of the size, concentration, and index of refraction of the suspended particles, in addition to any coating of particles on the TDL enclosure windows. Over time, the largest particles settle out of the detonation product gases first, leaving behind the smaller particles. Photographs taken a day after each event provide evidence that the gas purge system was always effective in keeping a significant portion of the windows sufficiently clean in the rib location. The overall similarities in the temporal trend of the transmittance suggest that the size distribution of particles produced in the detonations did not vary significantly (assuming the particle composition did not vary significantly). Note that the anomalous transmittance time trace of Beast is due to particle adherence to the windows. In interpreting the apparent magnitude of the transmittance between different experiments, we must account for sample volume dilution, which was greatest for Colossus due to increased purge gas flow rate for that experiment. Therefore, the total particulate loading implied by our measurements is greatest for Colossus, as would be expected.

Figure 9. Laser transmittance for the four detonation events measured in the rib emplacement. The signal for Polaris is nearly completely overlapped by that from Colossus.

Time-resolved measurements of carbon dioxide and water were successful using TDL, but we did not observe evidence for the presence of hydrogen cyanide in our sample volumes at concentrations greater than our detection limits under the test conditions. Grab samples did show the concentration of hydrogen cyanide to be very low and below the sensitivity of the TDL. Carbon monoxide was also observed just at the TDL detection limit. Figures 10 and 11 show the carbon dioxide concentrations measured by the TDL system in both the rib and invert enclosures during Beast and Colossus. The average concentration of carbon dioxide measured by TDL is approximately one half of that measured by the suite of real-time and grab gas measurements. The TDL device showed a high signal-to-noise ratio. The Colossus TDL data exhibited the same decrease in concentration at the continuous measurements, but unlike the continuous measurements the Beast TDL data remained constant throughout the measurement period.

In each case, the concentration of carbon dioxide measured in the invert device is much lower than measured at the rib. Should there be segregation of gases in the chamber it is expected that the hotter, carbon dioxide rich gas, would be higher in the chamber than the cooler, carbon dioxide poorer gas. This effect was observed in the gas measurements made by continuous monitoring with infrared sensors and mass spectrometry. However, the difference in concentration between the rib and invert was approximately 10% of the measured invert value, while the difference observed in the TDL instrumentation was approximately 400%.

Figure 10. Carbon dioxide concentrations measured during Beast in rib and invert locations.

Figure 11. Carbon dioxide concentrations measured during Colossus in rib and invert locations.

The greatest challenge with the TDL equipment proved to be maintaining adequate laser transmittance under conditions of high dust loading, due to a combination of dust in the sample volume and dust adhering to the windows. The highest probability of detecting transient molecular species (e.g., carbon monoxide, hydrogen cyanide) was just after the detonation, before combustion proceeded very far, and before significant dispersal occurred. However, this was also the time period of highest pressure and the most severe dust loading. Both of these features combined to decrease the sensitivity of the measurements. Laser transmittance during the critical time period of a demil event is likely to be the limiting factor for future application of laser-based measurements.

Los Alamos Aerosol Sampling System

The Los Alamos Aerosol Sampling System (LAASS) was used to measure aerosol concentrations and collect aerosol samples during demilitarization tests. The LAASS collects aerosol samples after the detonation by drawing aerosol-laden gas through the barrier into two parallel sampling systems. One system (impactor) collects aerosol samples from 10 to 0.1 μm in aerodynamic diameter and measures their mass concentrations ($\mu\text{g}/\text{m}^3$) in real time. The other system (streaker) collects three size fractions, $>10 \mu\text{m}$ (PM_{10}), $2.5\text{--}10 \mu\text{m}$, and $<2.5 \mu\text{m}$ ($\text{PM}_{2.5}$). The latter two size fractions are collected on rotating substrates thereby providing a time history of the aerosols present in the test chamber. The streaker samples are analyzed using Proton-Induced X-ray Emission Spectroscopy to determine the aerosol elemental composition for elements of atomic number greater than sodium ($Z=11$).

Figures 12 through 16 summarize impactor particle size distribution from the first three tests. No impactor data were obtained on the largest NEW test (Colossus). These data augment those collected by the standard TSP measurements in that discrete size ranges were monitored as a function of time. These data will be useful in evaluating computational models of the open detonation and dispersion process.

Figure 12. Banshee Impactor Size Distribution.

Figure 13. Polaris impactor size distribution.

Figure 14. Polaris impactor aerosol concentration vs time.

Figure 15. Beast impactor aerosol size distributions.

Figure 16. Beast impactor aerosol concentrations.

The LAASS operated successfully for most of the munitions shots and obtained data on aerosol size distributions and elemental concentrations for the small particle ($<10\ \mu\text{m}$) fraction of the aerosol population. Because of the lack of information on the expected aerosol concentrations prior to the tests, it took several shots to optimize the collecting strategy of both the impactor and streaker for the chamber conditions. The high aerosol concentrations necessitated taking grab samples at intervals rather than continuously monitoring the aerosols as originally expected. Size distribution and elemental concentration data were typically obtained from 10 min to 1 hr after the detonation.

The early time measured size distributions, measured by the impactor, are believed to be influenced by shock-induced aerosol removal from the blast mat and walls adjacent to the sampler, while later distributions showed the small particle “tail” of larger aerosols that contribute to the total particulate loading. Aerosol settling was significant within the measurement period, typically less than 1 hr. Except for the initial size distribution measurement, shifts of aerosol size distribution in the measured size regime were not observed. Measurements for longer times after the detonation would be necessary to study this.

Table 13 summarizes elemental concentration data from the streaker that were obtained on all tests. Aerosol metals concentrations indicate that most of the aerosols were composed of materials present in the chamber, including concrete, concrete aggregate, fiber-reinforced shotcrete, and tuff. Copper appears to be largely from that used in the projectiles.

The measured elemental concentrations in most cases agreed within an order of magnitude with those measured by Radian on the total aerosol fraction for Beast, indicating that elemental fractionation between fine and coarse aerosols did not occur. Measured total metal concentrations scaled well with the total explosive content of the shot.

Table 13. Total elemental concentrations from LAASS.

Test 1: Banshee—lower limit (µg/m³)									
Element	Sample 1 13 min	Sample 2 20 min	Sample 3 30 min	Sample 4 32 min	Sample 5 38 min	Sample 6 46 min	Sample 7 53 min	Sample 8 59 min	Sample 9 65 min
Sodium	0	0	0	0	0	0	0	0	0
Magnesium	0	0	0	0	0	0	0	0	0
Aluminum	1400	1019	925	712	741	592	576	334	358
Silicon	6560	4768	4181	3299	3437	2778	2718	1586	1104
Phosphorus	0	0	0	0	0	0	0	0	0
Sulphur	232	202	141	114	108	62	75	0	0
Chlorine	0	0	0	0	0	0	0	0	0
Argon	0	0	0	0	0	0	0	0	0
Potassium	797	582	471	400	378	377	296	176	118
Calcium	9488	7144	5376	4568	4300	4736	3520	2122	1474
Scandium	0	0	0	0	0	0	0	0	0
Titanium	181	134	109	95	84	106	69	41	22
Vanadium	0	0	0	0	0	0	0	0	0
Chromium	0	0	0	0	0	0	0	0	0
Manganese	80	44	34	31	29	35	23	14	7
Iron	4800	3638	2971	2686	2506	3170	2026	1205	694
Cobalt	0	0	0	0	0	0	0	0	0
Nickel	0	0	0	0	0	0	0	0	0
Copper	269	209	173	155	144	182	117	63	30
Zinc	125	97	82	73	66	86	52	29	17
Gallium	0	0	0	0	0	0	0	0	0
Germanium	0	0	0	0	0	0	0	0	0
Arsenic	0	0	0	0	0	0	0	0	0
Selenium	0	0	0	0	0	0	0	0	0
Bromium	2	3	2	3	1	2	2	2	0
Krypton	0	0	0	0	0	0	0	0	0
Rubidium	1	0	0	0	0	0	0	0	0
Strontium	17	12	10	10	10	11	8	5	3
Lead	20	15	11	11	9	14	7	4	1

Table 13. Continued

Test 2: Polaris—($\mu\text{g}/\text{m}^3$)													
	Samp. 1	Samp. 2	Samp. 3	Samp. 4	Samp. 5	Samp. 6	Samp. 7	Samp. 8	Samp. 9	Samp. 10	Samp. 11	Samp. 12	Samp. 13
Element	70 min	71 min	72 min	73 min	74 min	75 min	76 min	77 min	78 min	79 min	80 min	81 min	82 min
Sodium	0	0	0	0	0	0	0	0	0	0	0	0	0
Magnesium	0	0	0	0	0	0	0	0	0	0	0	0	0
Aluminum	1324	1221	1282	1163	1183	1090	1085	1083	1231	1146	1233	1187	1141
Silicon	6156	5742	6058	5516	5718	5231	5153	5088	5801	5436	5937	5715	5599
Phosphorus	0	0	0	0	0	0	0	0	0	0	0	0	0
Sulphur	247	233	268	220	230	203	208	209	237	250	255	234	206
Chlorine	38	0	0	0	0	0	0	0	0	0	0	62	0
Argon	0	0	0	0	0	0	0	0	0	0	0	0	0
Potassium	883	864	844	771	805	757	706	742	808	810	832	878	750
Calcium	8759	8929	8589	8321	8078	8103	7153	7737	8103	8565	8686	9222	8078
Scandium	0	0	0	0	0	0	0	0	0	0	0	0	0
Titanium	585	597	568	561	542	530	476	518	492	533	552	572	477
Vanadium	0	0	0	0	0	0	0	0	0	0	0	0	0
Chromium	0	0	0	0	0	0	0	0	0	0	0	0	0
Manganese	48	51	45	52	44	47	40	42	47	53	47	52	43
Iron	4572	4735	4402	4487	4161	4246	3720	4056	4085	4423	4355	4830	4015
Cobalt	0	0	0	0	0	0	0	0	0	0	0	0	0
Nickel	0	0	0	5	0	0	0	3	6	4	0	0	0
Copper	234	234	228	229	210	212	187	203	200	217	219	238	189
Zinc	132	140	129	130	121	118	104	113	113	127	127	130	104
Gallium	0	0	0	0	0	0	0	0	0	0	0	0	0
Germanium	0	0	0	0	0	0	0	0	0	0	0	0	0
Arsenic	2	3	2	2	2	3	2	2	4	4	8	2	2
Selenium	0	0	0	0	0	0	0	0	0	0	0	0	0
Bromine	3	3	3	4	2	3	4	2	3	0	0	3	4
Krypton	0	0	0	0	0	0	0	0	0	0	0	0	0
Rubidium	4	2	0	0	2	4	0	0	0	2	2	0	3
Strontium	19	21	19	20	19	23	17	19	20	18	19	21	20
Lead	12	15	12	13	12	14	12	12	10	11	0	12	11

Table 13. Continued

Test 3: Beast—($\mu\text{g}/\text{m}^3$)					
Element	Sample 1 7 min	Sample 2 19 min	Sample 3 32 min	Sample 4 49 min	Sample 5 64 min
Sodium	0	0	0	0	0
Magnesium	0	0	0	0	0
Aluminum	2864	1917	1646	1481	1397
Silicon	17881	11788	10049	8903	8462
Phosphorus	0	0	0	0	0
Sulphur	0	0	0	0	0
Chlorine	0	0	0	0	0
Argon	0	0	0	0	0
Potassium	2004	1327	1083	971	889
Calcium	14325	9360	7245	6381	5619
Scandium	0	0	0	0	0
Titanium	436	282	228	209	195
Vanadium	0	0	0	0	0
Chromium	0	0	0	0	0
Manganese	63	42	34	30	27
Iron	4785	3283	2660	2389	2134
Cobalt	0	0	0	0	0
Nickel	0	0	0	0	0
Copper	171	119	110	91	84
Zinc	91	60	49	45	42
Gallium	0	0	0	0	1
Germanium	0	0	0	0	0
Arsenic	1	2	3	2	1
Selenium	0	0	0	0	0
Bromium	35	21	18	17	15
Krypton	0	0	0	0	0
Rubidium	5	5	3	2	3
Strontium	40	27	20	18	17
Lead	15	5	4	3	5

Table 13. Continued

Test 4: Colossus—fine aerosol (<2.5µm) elemental concentrations (µg/m³)									
Element	Sample 1 7 min	Sample 2 14 min	Sample 3 23 min	Sample 4 33 min	Sample 5 43 min	Sample 6 53 min	Sample 7 63 min	Sample 8 73 min	Sample 9 83 min
Sodium	0	0	0	0	0	0	0	0	0
Magnesium	0	0	0	0	0	0	0	0	0
Aluminum	3318	2668	1900	1772	1489	1329	1269	1180	1190
Silicon	19256	14761	10530	9905	8606	7741	7525	6731	6660
Phosphorus	0	0	0	0	0	0	0	0	0
Sulphur	382	279	191	156	143	131	113	100	103
Chlorine	240	188	0	0	0	0	0	0	0
Argon	0	0	0	0	0	0	0	0	0
Potassium	2128	1466	1140	974	914	779	775	664	673
Calcium	8246	6082	4423	3991	3630	3245	3029	2693	2668
Scandium	0	0	0	0	0	0	0	0	0
Titanium	647	476	370	313	287	255	235	218	234
Vanadium	0	0	0	0	0	0	0	0	0
Chromium	0	0	0	0	0	0	0	0	0
Manganese	72	51	40	34	31	26	25	25	24
Iron	5722	4327	3221	2909	2548	2322	2094	1993	1977
Cobalt	0	0	0	0	0	0	0	0	0
Nickel	0	0	0	0	0	0	0	0	0
Copper	277	212	158	141	124	112	103	99	98
Zinc	235	179	137	121	106	97	87	88	82
Gallium	0	0	0	0	0	0	0	0	0
Germanium	0	0	0	0	0	0	0	0	0
Arsenic	0	0	5	0	4	5	0	2	3
Selenium	0	0	0	0	0	0	0	0	0
Bromium	4	4	3	4	2	3	0	0	0
Krypton	0	0	0	0	0	0	0	0	0
Rubidium	7	6	5	5	5	3	3	4	0
Strontium	22	18	12	11	11	11	8	8	9
Lead	24	17	0	11	0	0	0	5	4

Conclusions

Any conclusions drawn from these tests should be considered as preliminary. None of these tests were duplicated and there is no measure of the repeatability of the data. Although the original plan included two duplicate 24 projectile tests, for operational reasons subtle changes between the two 24 projectile tests were made that appeared to make a significant difference in the resulting emissions. In spite of these limitations, we can apply the following observations from these tests to formulate plans for future experiments in the X-tunnel test chamber.

Organic Emissions

In general, emissions of organic materials were very low. The vast majority of VOCs showed concentrations of <1 ppmv: only six individual compounds could be detected in amounts that exceeded 1 ppmv, and none exceeded 4 ppmv. Airborne SVOCs were measured between 1 and 100 mg/m³.

Organic materials in chamber residues were also quite small. Explosive residue was measured only in the six projectile test (Banshee), and no energetic materials were detected from the remaining NTS experiments. Very low levels of SVOCs were observed in the chamber residues. Most of the SVOCs identified showed concentrations of <100 µg/kg, and only two compounds showed concentrations of >1,000 µg/kg.

Metal Emissions

Measured total metal concentrations scaled well with the total explosive content of the shot. In general, metals detected in the residue and particulate samples were dominated by metals in the chamber and concrete. Metals such as calcium, magnesium and potassium, sodium, and titanium dominated the metals in the TSP samples and were derived only from concrete, fiber-reinforced shotcrete, and chamber rock. Aluminum was also found in the TSP and residue samples. Although there was a small amount of aluminum in the projectiles, the vast majority measured was derived from chamber materials.

There were significant increases in the concentrations of iron and copper in the TSP and residue materials above background levels found in the chamber materials of construction. Although much of the residue of iron and copper was derived from chamber materials there was an increase in concentration of these metals in the TSP samples due to contributions of metals in the projectiles. The Colossus experiment converted 0.01% of the copper in the experimental materials into total suspended particulates. The vast majority of the copper measured was from the projectile and not the clsc.

Recoveries of barium, chromium, and zinc were 5.5, 0.2, and 1%, respectively (uncorrected for background from the 60 projectile test). These recoveries were higher than for copper due to the contribution of these metals in the chamber materials. There were no metals in the residue samples that exceeded current regulatory TCLP limits.

Comparison of Two 24 Projectile Experiments

Two 24 projectile experiments were conducted: for one, the projectiles were placed on a steel plate on concrete; and the other, on a gravel bed. In general, emissions of products of incomplete combustion were reduced when the steel plate was used in these tests, as indicated by measurements of carbon monoxide, methane, hydrogen, and total nonmethane hydrocarbons. Emissions of individual VOCs or SVOCs were either lower or higher in each of the 24 projectile tests and did not show a clear pattern.

These data are generally consistent with the hypothesis that the gravel under the projectiles tends to quench the fireball and reduce completeness of combustion. Thus, the peak temperatures from the 24 projectile event conducted on a steel plate (Polaris) were higher than during the 24 projectile event conducted on gravel (Beast), and equilibrium pressures followed the same trend. The prompt pressure was also higher during Polaris indicating that the blast wave was reflected back by the steel plate and thus provided more energy to the fireball. A hotter fireball would be expected to produce a more complete afterburn resulting in lower concentrations of products of incomplete combustion. If the emissions of products of incomplete combustion are of interest, these results suggest they may be reduced by conducting the detonation in such a way that the amount of cratering is minimized. This hypothesis will, of course, need to be evaluated by further experimentation.

Tunable Diode Laser Measurements

The TDL sensor system was used for all four detonation experiments. From a mechanical standpoint the TDL equipment performed quite well. During severe ground motion and blast loading, we encountered no misalignment of optics, mechanical failures, or shrapnel damage. However, the data collected that could be used to evaluate these tests was minimal.

Los Alamos Aerosol Sampling System

The LAASS operated successfully for all of the munitions shots and obtained data on aerosol size distributions and elemental concentrations for the small particle ($<10\ \mu\text{m}$) fraction of the aerosol population. The high aerosol concentrations necessitated taking grab samples at intervals rather than continuously monitoring the aerosols as originally expected. Even so, this instrumentation provided a description of the particulates that was not available elsewhere. These data will be useful to model the amount and distribution of particulates from OB field events.

Elemental concentration data, from the particle collection device (streaker), were obtained on all tests. The measured elemental concentrations as measured by LAASS agreed within an order of magnitude with those measured by standard EPA procedures on the total aerosol fraction for Beast, indicating that elemental fractionation between fine and coarse aerosols did not occur.

List of Acronyms and Abbreviations

clsc	Copper linear shaped charge
EPA	Environmental Protection Agency
FY	Fiscal year
HE	High explosive
JDTP	Joint Demilitarization Demonstration Technology Program
LAASS	Los Alamos Aerosol Sampling System
ND	not detected
NEW	net explosive weight
NR	not reported
NTS	Nevada Test Site
OB	open burn
OD	open detonation
ppb	parts per billion
ppbv	parts per billion/volume
ppm	parts per million
ppmv	parts per million/volume
psia	pounds per square inch, absolute
psig	pounds per square inch, gauge
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
SNL	Sandia National Laboratories
SVOC	Semi-volatile organic compound
TCLP	Toxicity Characteristic Leaching Procedure
TDL	Tunable diode laser
TNT	2,4,6-trinitrotoluene
TO	Technical Order
TSP	Total suspended particulates
UNLV	University of Nevada, Las Vegas
VOC	Volatile organic compound

Appendix A

Resource for More Information

Sandia Fielded Tunable Diode Laser Apparatus

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Los Alamos Aerosol Sampling System

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Department of Defense/Department of Energy Joint Demilitarization Technology Demonstration Program Executive Summary of Phase I Demonstrations Detonation of Conventional Weapons: 155-mm High-Explosive M107 Projectiles

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