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**THE MEASUREMENT OF THE EXHAUST COMPOSITION
OF SELECTED HELICOPTER ARMAMENT**

By

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Fort Rucker, Alabama

JUNE 1967



DOCUMENT CONTROL DATA - R&D <small>(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)</small>		
1. ORIGINATING ACTIVITY <small>(Corporate author)</small> US Army Aeromedical Research Unit Fort Rucker, Alabama		2a. REPORT SECURITY CLASSIFICATION Unclassified
		2b. GROUP
3. REPORT TITLE THE MEASUREMENT OF THE EXHAUST COMPOSITION OF SELECTED HELICOPTER ARMAMENT		
4. DESCRIPTIVE NOTES <small>(Type of report and inclusive dates)</small>		
5. AUTHOR(S) <small>(Last name, first name, initial)</small> Scharf, P. B., Goshgarian, B. B. Nelson, H. M., US Air Force Rocket Propulsion Laboratory and Hody, G. L., US Army Aeromedical Research Unit		
6. REPORT DATE June 1967	7a. TOTAL NO. OF PAGES 38	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AFRPL-TR-67-203 USAARU-67-10	
b. PROJECT NO. 3AO 2560 1A 819	9b. OTHER REPORT NO(S) <small>(Any other numbers that may be assigned this report)</small>	
c. Task No. 051		
d.		
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited. Qualified requesters may obtain copies from the Defense Documentation Center (DDC), Cameron Station, Alexandria, Virginia		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY US Army Medical Research & Development Command, Washington, D. C. 20315	
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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Weapons Exhaust Composition Toxicology Armed Helicopters Carbon Monoxide Toxic Hazards Prediction						
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ABSTRACT

Crew members of armed helicopters are exposed to exhaust products of rapid fire machine guns and rockets. The exhaust composition of the weapons, needed for toxic hazard prediction, is difficult to obtain. In a joint Army-Air Force exploratory study, methods of analysis were evaluated and exhaust compositions for the 50 cal and 7.62mm machine gun and the 2.75" rocket were determined. A rapid scan infrared spectrophotometer was used for immediate examination of effluent gases in order to detect reactive species. The exhaust gases were analyzed at concentrations as high as 1000 times those present in helicopters to minimize the chance of missing any significant toxic product. A qualitative and quantitative analysis of gas phase and aerosol components is given. It may well be that the proportion of carbon monoxide in the exhaust is so high that permissible exposure times can be selected on the basis of its concentration alone while still limiting exposures to all other toxic materials to safe levels. However, significant amounts of nitrogen dioxide, ammonia, carbonyl sulfide, hydrogen cyanide, lead and copper were found. Their contribution to the toxicity of the weapons exhaust is now being evaluated and will be reported in a subsequent paper.

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ACKNOWLEDGEMENT

The authors are very grateful for the guidance and helpful advice administered "on site" by Dr. D. E. Beischer of the Naval Aerospace Medical Institute, Pensacola, Florida. The assistance and interest of Mr. R. C. Wands of the Advisory Committee on Toxicology, National Research Council, is also appreciatively acknowledged. The cooperative study could not have been initiated without the concern and efforts of Major O. Kittelstad now with the 6570th Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio.

EXPLANATION OF SYMBOLS

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
X	Any component of the exhaust products	None
A	Surface area of membrane filters	in ²
C _x	Air concentration of particulate component of exhaust products (means: concentration of product X)	mg/m ³
D	Particle diameter	μ (micron)
L _x	Membrane load of component X (weight of X per unit surface area of membrane)	mg/in ²
M _x	Weight of particulate component X (on a membrane)	mg
n	Number of particles (in given size range)	-
P	Pressure (final pressure)	mm Hg
P _a	Atmospheric pressure (at test site)	mm Hg
R	Ratio of gas component partial pressure to CO partial pressure	dimensionless
R _P	Ratio analogous to R for particles comparing particle concentration to carbon monoxide concentration	$\frac{\text{mg/m}^3}{10^6 \text{ PPM CO}}$
Q̇	Flow rate (gases)	L/min, ml/min
t	Time	sec, min
V	Volume (final volume)	ml, L
V _o	Volume (starting volume)	ml, L
[X]	Air concentration of component X	PPM (parts per million)

INTRODUCTION

Exposure to exhaust products of helicopter armament systems may be hazardous to the pilots and crews because the exhaust is toxic and their job is demanding. Two previous papers describe preliminary weapons exhaust measurement in helicopters¹ and an approach to further evaluation of the toxic hazard.² The exact exhaust composition is required for estimates of its toxicity and before permissible exposure parameters can be selected. After careful search of the literature did not produce suitable data² it was decided to measure the exhaust composition of three weapons typical of those in current use; two machine guns and the 2.75" rocket were selected.

All of the experiments were performed in an instrumented test stand which was essentially a laboratory environment. The use of delicate and bulky instruments was possible and concentrated gas samples, suitable for analysis of "trace gases", were obtainable by firing in a confined space. A rapid response infrared spectrophotometer was used at the test site to provide reliable analysis of reactive gases.

MATERIALS AND METHODS

TEST STAND DESIGN

Machine guns. Exhaust gases emerge from the gun muzzles in a narrow jet, at high pressures and flow rates, and are accompanied by a strong shock wave. In order to collect concentrated gas samples it was necessary to mount the machine guns in a stainless steel cylinder with their muzzles protruding through a teflon sheet into another cylinder (fig 1). During the initial experiment an aluminum sheet used to close the front cylinder was destroyed by the shock wave. It was replaced with a one half inch thick stainless steel plate. In about half of the experiments a baffle constructed from steel discs was inserted in the cylinder containing the weapon muzzle in order to improve turbulent mixing of the exhaust jet with surrounding air and to attenuate the shock wave (fig 2)*. It was also hoped that the baffle would provide a heat sink which would reduce unwanted burning of the trapped combustion gases. Provisions for purging the cylinder around the muzzle with clean nitrogen gas were available.

Rockets. Rocket motors were fitted with properly torqued inert warheads and were mounted on a static test stand (fig 3). The exhaust plume was directed into a steel tank twenty feet in length and eleven feet in diameter, located twelve feet in back of the rocket nozzle. Its opening can also be seen in fig 3.

SAMPLING METHODS

Gases. Gases and vapors were collected in evacuated flasks and with a condensation train. The installation of these devices is schematically shown in fig 1. The exhaust from the receiver and muzzle could be sampled independently with 500 ml capacity stainless steel sampling cylinders. Prior to each run, the sampling cylinders were heated to 50°C while undergoing continuous evacuation at 10 μ Hg absolute pressure. This cleanout process was checked by filling randomly selected cylinders with pure nitrogen which was then removed from the cylinders and analyzed with the mass spectrometer.

A rapid sequence timer was available to trigger the solenoid valves which then initiated collection at specified times after firing was begun³. The duration of sampling could also be controlled by the timer and was kept sufficiently long to insure that the samples were obtained at atmospheric pressure (usually about 2 seconds). A pressure transducer near the gun muzzle provided additional timing information.

*Design provided by Dr. C. Sabin; Geoscience Ltd, Solana Beach, California

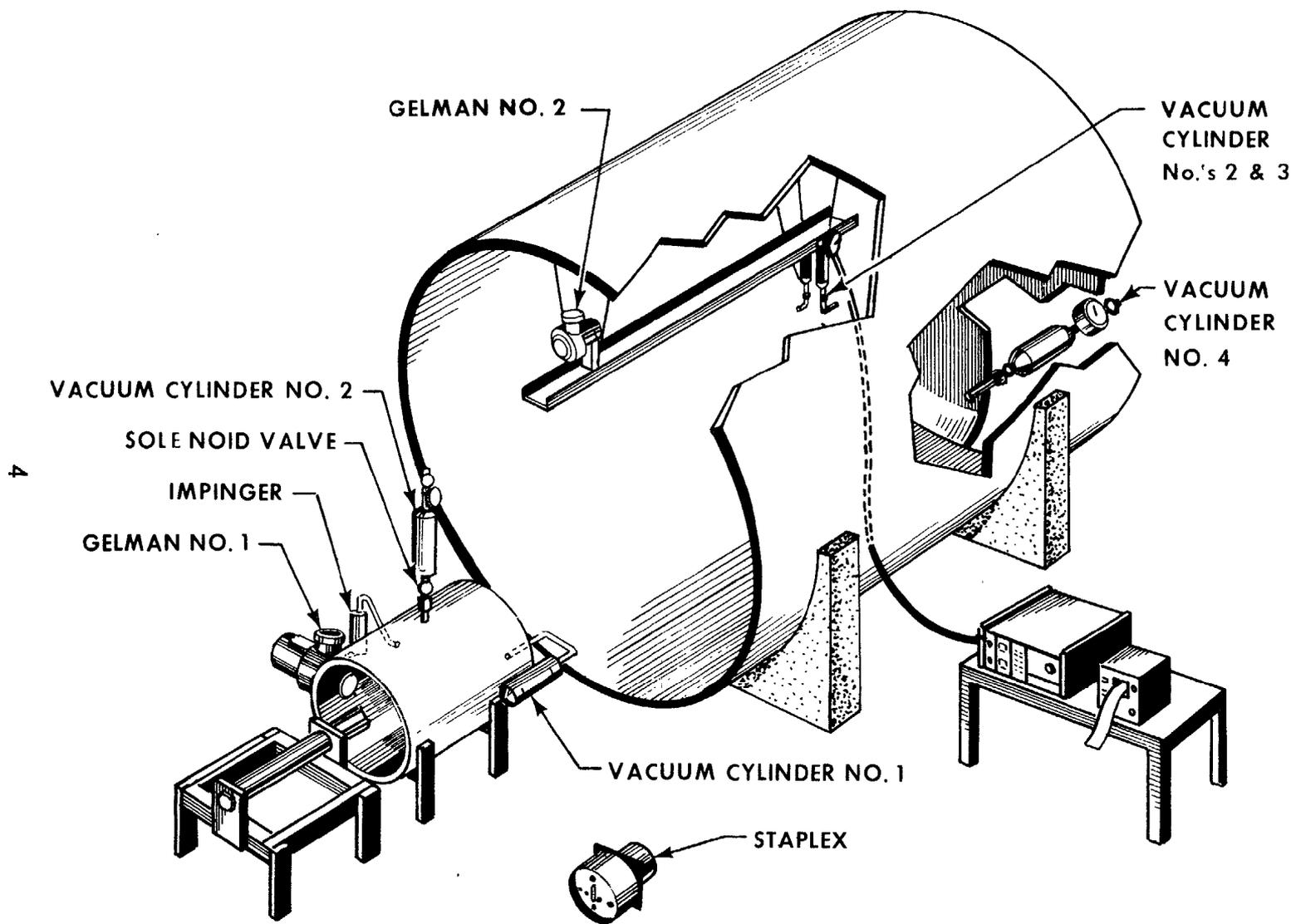


Fig 3a. Rocket test stand schematic

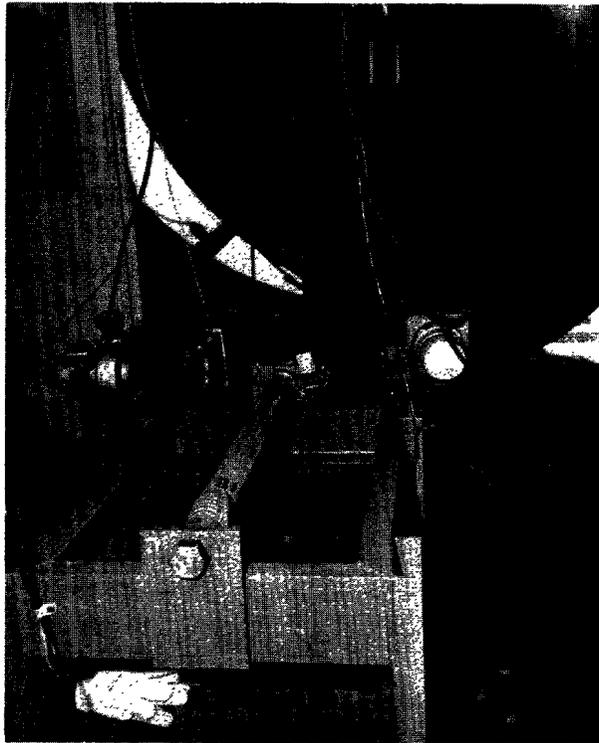


Fig 3b. Rocket test stand

During selected firing runs, gas from the guns was ducted through stainless steel tubing to a condensation train. Each stage of the train was constructed from a monel cylinder filled with glass beads. The first stage was immersed in a mixture of salt water and ice, the second was in dry ice and trichloroethylene and the third in liquid nitrogen. Flow through the train was maintained at a rate of approximately 7 L/min by a diaphragm pump. After sampling had been completed, the three traps were stored at liquid nitrogen temperature pending analysis.

Rockets. Rocket exhaust was also obtained in evacuated cylinders closed with solenoid valves. However, three liter cylinders were substituted for the 500 ml because the gas samples were expected to be relatively dilute. The interior of the large cylinders was made to reach atmospheric pressure within 2 seconds after opening by the use of high throughput solenoid valves. During several firings, a cylindrical shroud was placed immediately in back of the rocket nozzle in order to simulate flight conditions by increasing the airflow around the rocket. Gas samples were obtained from the steel tank in back of the rocket and from a probe, six feet downstream from the nozzle, six inches off the longitudinal axis of the rocket.

In the experiments, working curves (transmittance vs partial pressure) were drawn from results obtained with CO, CH₄, NH₃, carbon dioxide (CO₂), and nitrogen dioxide (NO₂) standards brought to total pressures of 250mm Hg by the addition of pure nitrogen. Thus, samples measured at pressures different from 250mm Hg would be somewhat in error. The pressures at which infrared absorption was actually measured can be calculated from the starting pressures of the samples, and the sample and absorption cell volumes. The machine gun exhaust products were obtained at 680mm Hg total pressure* and in a 500 ml volume. The internal volume of the one meter gas cell in the Perkin-Elmer 421 is one liter: The simple gas law relationship:

$$P = P_o \frac{V_o}{V} \quad (1)$$

gives the final sample pressure, P, in terms of the starting pressure, P_o; starting volume, V_o, and the final volume, V. Thus

$$P = 680\text{mm Hg} \times \frac{500 \text{ ml}}{1500 \text{ ml}} = \text{appx } 227\text{mm Hg} \quad (2)$$

V in this case is the combined volume of the sampling cylinders and the one meter cell when these are joined. For these samples, pressure broadening did not impair accuracy. The rocket gas samples obtained in 3 liter cylinders yielded final pressures of

$$P = 680\text{mm Hg} \times \frac{3000 \text{ ml}}{4000 \text{ ml}} = 510\text{mm Hg} \quad (3)$$

For these, the use of working curves derived at 250mm Hg will result in some error. Nevertheless, the accuracy desired did not warrant preparation of additional standards. Partial pressures reported have been corrected for the appropriate expansion factor so that they will represent pressures present at the test site in the undisturbed combustion products.

Working curves were not prepared for water because it has no toxicological importance and it is inconvenient to pick an analytical band out of the rotational fine structure. Although not reported in detail, estimates of the partial pressure of water were made by visual comparison to standard curves and can be obtained from the authors on request.

*Atmospheric pressure at the test site was 680 ± 10mm Hg.

No quantitative estimates are reported for species identified in the condensation train because of the undetermined and variable efficiency of the traps.

Mass spectrometer analysis. A small quantity of sample was expanded to approximately $200\ \mu\text{Hg}$ absolute pressure in a three liter vessel, and then was passed through a variable leak valve into the instrument. This gave source pressures of about $2 \times 10^{-6}\text{mm Hg}$ (low source pressures are desirable to preclude ion-molecular reactions which would have complicated the data reduction).

A Consolidated Electrodynamics Corporation model 21-110 high resolution mass spectrometer was used to make the measurements. Photographic plate ion detection was used to permit extended ion exposure and to provide for trace component detection. Quantitative analysis was obtained by making successive ion exposures with increasing exposure times. Lightly exposed (short exposure time) lines could then be associated with corresponding darker (longer exposure time) lines in consecutive spectra until all ion lines of interest had been correlated. Component concentrations were then calculated from the ion line densities using plate emulsion calibration curves, ion line widths, and component sensitivity. The accuracy of the measurement is related to the partial pressures. For partial pressures as low as 10mm Hg an accuracy of $\pm 10\%$ was obtained. Between 1 and 10mm Hg it was $\pm 50\%$ and for components below 1mm (0.1% of sample) it was $\pm 100\%$.

To identify species, atomic masses were assigned to corresponding ion lines by measuring the ion line distances from standard lines on the same spectrum. Identification of the unknown lines to ± 0.005 atomic mass units was made by computer-assisted analysis of the measured distances and their relationship to the masses of the standards. The high resolution permitted easy differentiation of nitrogen and CO at mass 28, for example. Cracking patterns or mass spectrometer "finger prints" for molecules were also helpful in identifying species. Because the initial analysis required only a three liter sample at $200\ \mu\text{Hg}$ absolute pressure, the majority of the sample remained. This remaining portion was slowly evacuated through a glass bead filled, liquid nitrogen cooled, glass trap. Flow rate was maintained at about 500 ml/min ($1\ \text{ft}^3/\text{hr}$) until all sample gas had passed through the trap resulting in increasing vessel vacuum and decreasing flow. The glass trap was then immersed in a dry ice and acetone bath (-79°C) and the materials volatilized at that temperature were analyzed by the mass spectrometer method already outlined. Finally, the trap was fully evacuated at -79°C and warmed to $+20^\circ\text{C}$ at which time the effluent gases were again introduced into the mass spectrometer. By these concentration and fractionation steps data were obtained on the nature of trace components in the combustion gas sample.

Infrared analysis (rapid scan). A Beckman IR 102 spectrophotometer was installed in proximity to the weapons in order to minimize the delay between sample

Further examination of certain membranes was done to detect adsorbed gases. Portions of these selected membranes were inserted directly into an oven attached to the low volume inlet of a mass spectrometer. Gases evolving from the specimens at temperatures of 100 to 200°C were analyzed. Finally, measured portions of the membranes were solvated and analyzed for inorganic materials by atomic emission spectroscopy.

SIMULATION

Laboratory burning of propellant was limited to a brief effort designed to alert the chemists to the nature of species to be expected in definitive tests. Propellant was burned in an apparatus constructed from a 75 ml stainless steel cylinder which was filled with air at 1 atmosphere pressure. One end of the cylinder was fitted with a valve and pressure gauge and the other with a combustion chamber machined from a 3/8" to 1/4" reducing swage-type tubing connector. The combustion chamber was sealed on the side toward the cylinder with heavy gauge aluminum foil which acted as a 100 psi burst diaphragm. Ignition was initiated by passing an electric current through a nichrome wire in the connector. A pressure surge accompanied ignition after which the diaphragm fractured, expanding the combustion gases into the known air volume. The products of combustion were analyzed with the mass and infrared spectrometers. Gun propellant, which burned poorly in the combustion chamber, was loaded into a 30.06 caliber cartridge and the bullet was then fired with a conventional rifle through a double ended steel cylinder of one liter capacity which had been placed close to the muzzle. The ends of the cylinder were then quickly capped and the contents were analyzed in the laboratory in the usual manner. Finally, rocket propellant was fired in a micro-rocket of a few grams capacity and the collected exhaust gases were also analyzed.

SAFETY

All weapons and sampling devices were electrically activated from a safe remote location. After bore sighting, the guns were mounted with stainless steel clamps provided with butyl rubber inserts which permitted a limited play during recoil. Bullets were arrested by a twenty foot thick sand bag barrier contained in a thick walled steel tank. Conventional rocket test safety procedures were employed with the 2.75" FFAR and stringent precautions to avoid premature ignition of the rocket motors were included.

CONTROL OF SAMPLING AND ANALYSIS METHODS

The sampling and analysis methods for CO, CO₂, CH₄, NH₃ and NO₂ were tested as realistically as possible without omitting any step or delay in the

procedure. First, gas mixtures were generated in the steel cylinder used to house the guns (fig 1). After the samples were carried through all of the analytical procedures previously described (except condensation) the measured partial pressures obtained were divided by the partial pressures actually introduced to obtain a recovery parameter expressed as percent:

$$\text{"Recovery"} = \frac{\text{partial pressure measured}}{\text{partial pressure introduced}} \times 100 \quad (40)$$

Reliable recovery was demonstrated for CO, CO₂ and CH₄ but, the results with NO₂ and NH₃, were poor (Table 2). This result suggested the possibility that NO₂ and NH₃ were disappearing via a rapid reaction with each other. This question was resolved with the help of the IR 102 which was shown to be capable of simultaneous NO₂ and NH₃ detection.

EXPERIMENTAL CONDITIONS			RECOVERY (%)			
Material	Volume Fraction (%)	Partial Pressure (mm Hg)	INFRARED		MASS SPEC	
			Exp 1	Exp 2	Exp 1	Exp 2
CO	5	34	108	88	102	138
NH ₃	0.1	0.68	0	0	19	44
NO ₂	0.05	0.34	30	53	0	0
CO	5	34	85			
NH ₃	0.5	3.4	33		INOPERATIVE	
NO ₂	0.05	0.34	0			
CO	20	120	65		113	
CO ₂	5	30	63		100	
CH ₄	0.16	1	170		110	

Table 2. Recovery of Known Gas Mixtures

SAMPLE PRESSURE

The gas samples were obtained at a total pressure of one atmosphere, including the contributions of the weapons exhaust and incidentally trapped air. The amount of weapons exhaust in the sample is reflected in the sum of partial pressures of the sample components. In practice, this limits consideration to those materials seen by the analytical instruments. However by mass spectrometry, argon content can be established and the partial pressure exerted by the air component of the sample can then be calculated. The pressure of the exhaust gas component is obtained by subtraction from atmospheric pressure. Comparable results were obtained from both methods, confirming that the major constituents of the exhaust gases (those contributing significant pressure) were measured adequately. Average sample partial pressures (calculated by both methods) appear in Table 4 along with corresponding partial pressures of CO (pCO).

LOCATION	TOTAL PRESSURE OF EXHAUST COMPONENTS (mm Hg)				PARTIAL PRESSURE OF CARBON MONOXIDE (mm Hg)			
	INFRARED		MASS SPEC		INFRARED		MASS SPEC	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
50 cal muzzle	92-180	130	45-270	150	65-130	94	38-210	110
50 cal receiver	15- 28	22	No Data		6- 14	11	No Data	
7.62 mm muzzle	6-300	130	49-210	140	5-200	88	34-170	110
7.62 mm receiver	20- 92	51	35 (1 sample)		13- 52	30	27- 63	45
Rocket (Probe)	60-120	70	32- 91	61	14- 55	30	16- 52	32
Rocket (Tank)	13- 56	33	37 (1 sample)		1- 17	7	15 (1 sample)	

Table 4. Partial Pressure of Samples and of CO

GAS AND VAPOR ANALYSIS

Twenty-six compounds were identified in the weapons exhaust (Table 5). The first ten will be evaluated as potential toxic hazards while the last sixteen are either relatively non-toxic or so diluted that they are judged of no interest. The methods preferred for the detection of each material are also indicated. Three of the compounds, Freon, acetone and trichloroethylene are probably present as laboratory artifacts. The "miscellaneous light hydrocarbons" range from C2 to C7 in length.

The complete list of partial pressures of each component is unavoidably cluttered (Appendix 2). A dimensionless ratio, R, which compares the partial pressure of each component with that of CO in the same sample is given. For any compound "X", "R" is calculated from pX and pCO by the elementary relationship:

$$R = \frac{pX}{pCO} \quad (5)$$

Multiplication of R by 10^3 simplifies presentation. It also incidentally provides a quantity numerically equal to the concentration of X (in PPM) present for each 1000 PPM of CO. Average and maximum R is presented for each weapon for the nine gases in addition to CO which are of particular interest (Table 6).

PARTICLE ANALYSIS

Size Distribution. There is no single presentation of particle size distribution which is entirely satisfactory. The actual particle count is displayed on a log-probability plot (fig 7). For any point, the ordinate is the particle diameter and the abscissa is the number of particles (in percent of those counted) which have a diameter less than the ordinate value. The volume at each size range is perhaps a better indication of "dose". It was calculated assuming a spherical particle:

$$V_p = n \left[\frac{1}{6} \pi D^3 \right] \quad (6)$$

Where D is the particle diameter and n the number of particles of diameter D (see fig 8). Finally, the cumulative volume of particles less than a given diameter is presented as a function of diameter (fig 9). In all cases representative runs rather than average values are shown. In fig 8, the curves are arbitrarily stopped at a diameter a little over 10μ above which they have probably no meaning. V increases as D^3 and at higher values a single particle may have more volume than

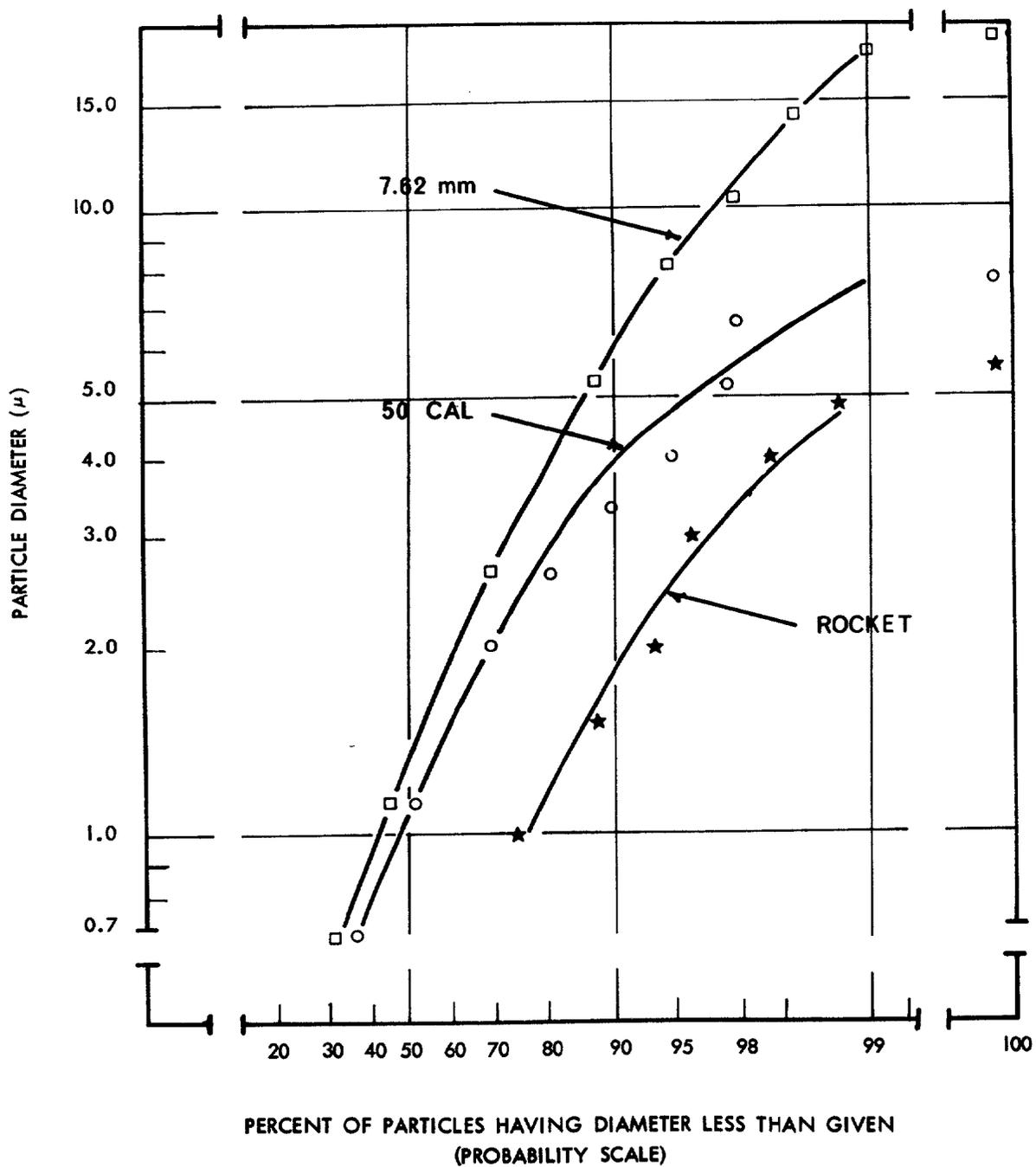


Fig 7. Particle size analysis
(log/probability plot)

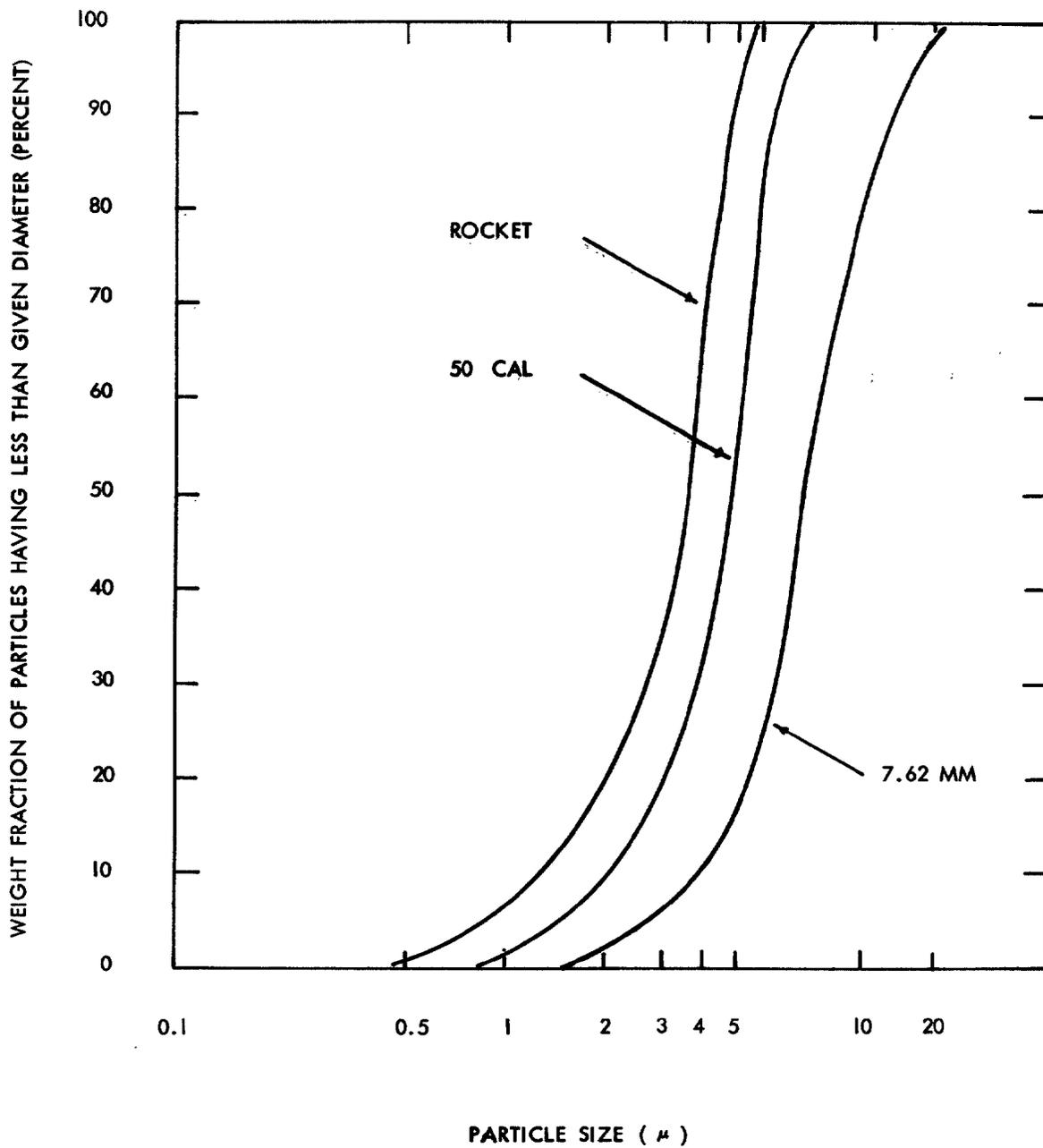


Fig 8. Particle size analysis
(cumulative volume as a function of size)

A ratio analogous to "R" in the gas measurement case can be calculated for comparison of particulate concentration to the concentration of carbon monoxide. For each particulate component X a ratio of its concentration to that of carbon monoxide can be expressed:

$$R_p = \frac{C_x}{\frac{pCO}{P_a}} \quad (12)$$

Where R_p is the desired ratio, and the pCO was measured for the same run as the particular C_x . P_a is the atmospheric pressure. pCO/P_a is thus the volume fraction of CO present with C_x . Division by 10^3 facilitates presentation and gives a quantity numerically equal to the C_x present for each 1000 PPM of CO. $R_p \times 10^{-3}$ can be thought of as having units mg/m³ of X per 1000 PPM CO. Calculation is simplified because of the relatively constant $P_a = 680 \pm 10$ mm Hg. Thus

$$R_p = \frac{C_x}{pCO/680} = 680 \frac{C_x}{pCO} \quad (13)$$

R_p is given for all elements measured by emission spectrometry (Table 7). It should be noted that the carbon monoxide measurements used in the calculation of R_p are not as accurate as those used to calculate the "R" parameter for gases. Partial pressures of CO and that of compounds being used to calculate R for gases were obtained from the same samples while the particle samples were obtained at slightly different locations within the apparatus. For the calculations of R_p estimates of pCO averages for the run were used.

ABERRANT RUNS

Two experiments revealed gas composition strikingly different from those obtained on all other runs. They produced the only samples in which NO₂ could be demonstrated and the CO₂/CO ratio was very high. The detailed analysis of these runs is compared to "typical" runs with the same exact weapons and firing conditions (Table 8).

Run 12 50 caliber machine gun			
CO concentration appx 88,000 PPM (pCO = 60 mm Hg)			
Flowrate (\dot{Q}) = 8 ft ³ /min			
Element	Membrane Load (mg / in ²)	Air Conc in sampling Area (mg / m ³)	R _p × 10 ⁻³
Cu	.54	350	4.3
Pb	.18	110	1.3
Zn	.10	64	0.7
Ca	.12	76	0.8
Al	.04	25	0.3
Fe	.008	5.1	0.06
Si	.007	4.4	0.05
Mg	.001	0.6	0.007

Run 20 7.62 mm machine gun			
CO concentration appx 150,000 PPM (pCO = 100 mm Hg)			
Flowrate (\dot{Q}) = 9 ft ³ /min			
Element	Membrane Load (mg / in ²)	Air Conc in sampling Area (mg / m ³)	R _p × 10 ⁻³
Cu	.32	180	1.2
Pb	.10	56	0.4
Zn	.04	23	0.2
Ca	.04	23	0.2
Al	.02	11	0.07
Fe	.008	4.5	0.03
Si	.003	1.7	0.01
Mg	.001	0.6	0.004

Run 28 Rocket			
CO concentration appx 14,700 PPM (pCO = 10 mm Hg)			
Flow Rate (\dot{Q}) = 18 ft ³ /min			
Element	Membrane Load (mg / in ²)	Air Conc in sampling Area (mg / m ³)	R _p × 10 ⁻³
Fe	4.6	1300	88
Al	0.4	28	2.0
Ca	-	-	-
Mg	0.02	5.6	0.4
Si	0.05	14	1.0
Pb	2.8	790	53
Cu	0.13	37	2.6

Table 7a. Calculation of R_p for typical runs

Component	$R = \frac{pX}{pCO}$ (maximum)	Maximum Concentration at 1000 PPM CO (PPM)	TLV (PPM)
Acetylene	0.01	10	> 1000
Ethylene	< 0.01	10	> 1000
Methane	0.14	140	> 10,000
Methanol	< 0.001	1	> 100
Hydrocarbons C2-C7	< 0.001 (trace)	1	> 100
Benzene	< 0.0001	0.1	> 10

Table 9. Comparative toxicity and concentrations of six gas phase components

available statistical tool, analysis of variance, unfortunately could not be applied to the problem because the experimental design was that of a screening study. The level of initial planning did not provide sufficient control of the large number of variables and the number of available samples does not permit meaningful statistical treatment.

Certain conclusions follow intuitively from a simple look at the data. Much larger relative concentrations of CO₂, HCN, CN, lead, and iron distinguish the rocket from either of the guns. On the other hand the two types of machine guns gave results which were very similar, especially when the variability from weapon to weapon is compared to the differences in composition from run to run. These inter-run differences are particularly striking for two runs which displayed very high CO₂/CO ratios and were the only ones in which NO₂ was detected (Table 8). Due to instrument difficulties the mass spectrometer was unavailable during both of the experiments, and the IR 102 was inoperative for run 15. Also only a 10 cm path gas cell was available instead of the usual 30 cm path for run 5. The 50 cal machine gun was used in run 5 and the 7.62mm in run 15. Although several additional runs were made under identical conditions, the results obtained in these two atypical experiments could not be reproduced. Variation in propellant

composition and packing density is common because the most rigid specifications for ammunition are ballistic rather than chemical. Perhaps different propellant compositions or a transient and inapparent weapon malfunction accounted for the unusual results. The extremes of CO₂ and NO₂ concentration noted will nevertheless have to be considered in any specific toxic hazard evaluations based upon this study.

The question of distorted results due to secondary burning of concentrated exhaust in the sampling area surrounding the muzzle was approached by firing in nitrogen. Again the use of a statistical comparison would be desirable but while this is impossible, the results show no obvious differences in runs fired in nitrogen (see Appendix 1 and 2). It was also noted that while the mixture around the muzzle and receiver of the guns did frequently "explode" during firing, the explosions were late events in the firing sequence and gas samples were obtained early. The exhaust composition of the receiver and muzzle did not obviously differ though again the data were insufficient for statistical analysis.

In the light of hindsight some suggestions and recommendations for future studies of new armament systems can be made:

1. Propellant combustion in the laboratory under closely simulated burning conditions is a desirable first step with new propellant systems but not with systems closely related to those already investigated. It will almost certainly be impractical to simulate the "real" system closely enough to obtain highly accurate predictions although simulation is helpful in learning the nature of the species that can be expected.

2. In experiments which require weapons firing, statistical consultation to develop the necessary research design is considered an absolute requirement. The experimental design must provide for rigid control of the variables related to the weapon, ammunition and sampling system. Considerable scatter in the data is to be expected and its sources must be identified if the results are to be efficiently reported and employed.

3. It is essential to control both sampling and analysis by the use of known samples prepared from standards and submitted to the exact analytical scheme from start to end.

4. Specific instrumentation for the more reactive species expected must be available on site for examination of samples without delay.

5. All equipment exposed to the shock wave (guns) or thermal effects (rocket) must be resistant. Test stand components, of course, have to be

LIST OF MANUFACTURERS

Beckman Instruments Inc.
Fullerton, California

Consolidated Electrodynamics
Division Bell and Howell Company
Pasadena, California

Gelman Instrument Company
Ann Harbor, Michigan

GRI Inc.
Washington, D. C.

Millipore Corporation
Bedford, Massachusetts

Perkin Elmer Company
Norwalk, Conn.

Staplex Company
Brooklyn, New York

W. Wahl Corporation
Santa Monica, California

Appendix 1. Schedule and description of the experiments

RUN DESIGNATION	NUMBER OF ROUNDS FIRED	REMARKS	INSTRUMENTS USED				
			IR 102	CONV IR	MS	COND TRAIN	PARTIC SAMPLE
50 CALIBER FIRINGS							
1	2	Preliminary experiments, Detailed results are not reported Results are not considered in statistical analyses	-	X	-	-	-
2	3		-	X	-	-	-
3	4		-	X	-	X	-
4	10		-	X	-	X	-
5	7	aberrant run, results are reported separately and not included in statistical summaries. End closure and condensation train made available on subsequent runs.	X	X	-	X	-
6	19		X	X	X	X	-
7	14	Fired with muzzle in nitrogen atmosphere.	-	X	X	X	-
8	20	Same as #7.	X	X	-	-	X
9	20	Pressure transducer installed for continuous record.	-	X	X	X	X
10	17	Stoppage after first 2 rounds.	X	X	X	X	-
11	6		X	X	X	X	X
12	35		-	X	X	X	X
13	1	Purpose of run was to obtain dilute particulate sample.	-	-	-	-	X
14	15	Probable muzzle flash occurred.	-	X	-	-	-

Appendix 2 (Cont'd)

RUN	LOC CODE	INST CODE	TOTAL SAMPLE PRESS.	CO Partial Press	CO ₂		CH ₄		NH ₃		NO ₂		HCN		C≡N		CH ₃ CHO		SCO		C ₆ H ₆		C ₂ H ₂				
					P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R			
2	MUZ1	IR	68	45	18	400	0.6	13	0.15	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Note 1	
3	MUZ1	IR	71	45	20	430	0.5	10	0.30	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Note 1	
4	MUZ1	IR	93	32	55	1700	0.5	14	0.15	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Note 1	
5	MUZ1	IR	180	14	170	12000	-	-	-	-	0.09	7	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ	102	-	~10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
6	MUZ	102	-	~80	-	-	-	-	~1	~13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ5	IR	140	98	36	370	1.1	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ1	M	160	120	24	200	1.2	10	0.41	4	-	-	0.14	1	0.01	0.1	-	-	-	-	-	-	-	0.7	0.6		
7	MUZ1	IR	150	99	38	380	1.4	14	0.45	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Note 2	
	MUZ3	IR	180	130	48	380	1.5	12	0.75	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ5	IR	120	83	32	380	1.1	13	0.36	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ3	M	240	160	45	290	0.7	5	0.41	4	-	-	0.04	0.3	0.08	0.5	1.5	10	0.03	0.1	-	-	-	0.07	0.4		
8	MUZ1	IR	92	65	23	360	0.8	12	0.51	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Note 2	
	MUZ3	IR	150	110	40	380	1.3	12	0.90	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ5	IR	100	73	26	350	0.8	10	0.80	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ	102	-	~200	-	-	-	-	~2	~10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
9	MUZ3	M	45	38	6	170	0.2	6	0.03	0.8	-	-	0.01	0.4	-	-	0.01	0.4	-	-	-	-	-	-	0.02	0.6	Note 3
	MUZ	102	-	300	-	-	-	-	~2	~7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
10	RCV	IR	15	6	6	1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ3	M	270	210	60	280	2.5	12	0.2	1	-	-	0.01	0.05	0.03	0.2	0.14	0.5	0.02	0.1	-	-	-	0.14	0.5		
11	RCV	IR	19	8	5	690	0.09	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ3	M	110	88	20	230	0.14	2	0.02	0.2	-	-	0.007	0.07	0.003	0.04	0.007	0.04	-	-	-	-	-	-	0.014	0.2	
	RCV	102	-	~10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
12	RCV	IR	26	14	9	640	0.09	7	0.03	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
	MUZ3	M	80	62	18	280	0.34	5	0.03	0.5	-	-	0.03	0.5	0.01	0.2	0.03	0.5	0.007	0.1	-	-	-	0.04	0.7		
14	RCV	IR	28	14	11	790	0.03	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		

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Appendix 2 (Cont'd)

RUN	LOC CODE	INST CODE	TOTAL SAMPLE PRESS.	CO Partial Press	CO ₂		CH ₄		NH ₃		NO ₂		HCN		C=N		CH ₃ CHO		SCC		C ₆ H ₆		C ₂ H ₂	
					P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R
15	MUZ1	IR	25	5.4	18	3300	-	-	-	-	0.12	22	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ3	IR	27	3.6	22	6100	0.03	8	-	-	0.09	25	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ5	IR	19	5.7	13	2300	0.03	5	-	-	0.06	11	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	8.4	1.8	4	2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	MUZ1	IR	6	4.5	2	330	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ5	IR	9.6	5.7	4	680	0.06	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	49	30	12	400	0.66	22	0.33	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ3	M	49	34	7	220	0.48	15	0.07	2	-	-	0.05	2	0.01	0.3	0.06	2	0.002	0.04	0.001	0.02	0.05	2
17	MUZ1	IR	170	96	52	540	2.3	23	0.15	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	44	21	13	610	0.4	19	0.27	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ3	M	170	130	33	270	1.4	12	0.07	0.6	-	-	0.03	0.3	0.03	0.3	-	-	0.003	0.03	0.002	0.02	0.05	0.4
	MUZ	102	-	~200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	MUZ1	IR	180	120	42	360	2.1	16	0.48	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	66	36	17	460	0.8	21	0.51	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ	102	-	~100	-	-	-	-	1	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	MUZ5	IR	130	90	30	330	1.5	17	0.33	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	75	45	20	430	0.8	17	0.45	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	92	52	24	460	0.8	16	0.70	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	102	-	~30	-	-	-	-	1	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	MUZ1	IR	170	110	40	350	2.2	20	0.33	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ5	IR	110	80	26	330	1.6	20	0.12	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	56	34	15	430	0.8	22	0.57	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	31	20	8	410	0.4	19	0.27	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ5	M	140	110	29	260	1.3	11	0.20	2	-	-	0.07	0.7	0.14	1.4	-	-	0.03	0.3	-	-	0.07	0.7
	RCV	M	-	63	18	290	1.1	17	0.14	2	-	-	0.07	1.2	0.14	2.0	-	-	0.05	0.8	-	-	0.07	1.3
21	MUZ1	IR	300	200	75	360	1.9	9	0.30	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ5	IR	130	84	36	430	0.9	11	0.18	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	24	13	8	580	0.12	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	IR	20	13	8	600	0.09	7	~0.01	~2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MUZ3	M	210	170	35	220	1.4	9	0.14	0.8	-	-	0.11	0.7	0.03	0.20	-	-	-	-	-	-	-	-
	RCV	M	35	27	8	270	0.5	19	0.27	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	RCV	102	-	~20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note 2

Note 2

Note 4