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VEHICLE DETECTION CLASSIFICATION USING CHEMICAL SENSORS

R. P. Murrmann, et al

Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

August 1972

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C. S. Harden, J. C. Chalcraft and O. Renius

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C. S. Harden, J. C. Chalcraft and O. Renius

August 1972

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PROJECT MANAGER, REMBASS, FORT MONMOUTH, N.J.
BY
U.S. ARMY COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

EDGEWOOD ARSENAL
EDGEWOOD ARSENAL, MARYLAND

U.S. ARMY TANK-AUTOMOTIVE COMMAND
WARREN, MICHIGAN

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PREFACE

This study was conducted by the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), in cooperation with Edgewood Arsenal, and the U.S. Army Tank-Automotive Command, for the Project Manager, Remotely Monitored Battlefield Sensor System (REMBASS), Fort Monmouth, N.J., under Task No. SMO 72-0570-06-02, *Trace Gas Detector Study*. The general objective of the work was to provide a technical assessment of the possibilities for vehicle detection/classification using various types of chemical sensors.

Overall coordination of the study was provided by Dr. R.P. Murrmann, Research Chemist, USA CRREL. Other USA CRREL participants included Mr. T.F. Jenkins, Chemist, assisted by Mr. B. Brockett, Physical Science Technician, and 1LT. W. O'Reilly, Chemist. The work at Edgewood Arsenal was coordinated by Mr. L.G. Appel, Electronics Engineer, with input from Dr. C.S. Harden, Research Chemist, and Mr. J.C. Chalcraft, Electronics Engineer, who were assisted by Mr. R.A. Miller, Electronics Technician, and Mr. H.A. Smith, Jr., Engineering Technician. Personnel at USATACOM included Mr. O. Renius, Research Physicist, who was assisted by Mr. W. Bremerkamp, Engineering Technician, and Mr. D. Abbas, Physical Sciences Assistant.

This report was reviewed by Mr. H. Stevens, Research Civil Engineer, USA CRREL, and Mr. E. Engquist, Chief, Detection and Alarm Branch, DED, Edgewood Arsenal.

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13. ABSTRACT
The concept of using chemical sensors for remote surveillance of vehicle activity was evaluated through field and laboratory studies, and consideration of the state of the art of current chemical sensor concepts. Reliable detection of vehicles was found to be feasible at downwind ranges up to several hundred meters depending on the type of chemical sensor employed. By use of a two-sensor array, detection independent of wind direction was highly successful at reduced detection range. False-alarm rates in remote areas were virtually zero due to low levels of exhaust chemicals in ambient air. Potential was shown for classification of diesel and gasoline vehicles by using a classifier unit consisting of two detectors. By trade-off analysis, it was determined that the condensation nuclei, surface adsorption, and Honeywell ionization sensors showed most immediate promise for development as vehicle detectors. Recommendations were made on additional work required in development of chemical sensors for Remotely Monitored Battlefield Sensor System (REMBASS) applications.

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Infrared absorption detector						
Kryptonate detector						
Mass spectrometer						
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Surface adsorption detector						
Thermal conductivity detector						
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by

R.P. Murrmann, T.F. Jenkins, L.G. Appel, C.S. Harden, J.C. Chalcraft and O. Renius

INTRODUCTION

Objects or activities of military significance can be detected by sensing associated chemicals in the atmosphere. Perhaps the oldest and best recognized use of this concept is the development of alarm systems for various types of toxic chemical agents. Another well publicized example is the development of the personnel detector that is sensitive to combustion product particulates generated in conjunction with personnel activities. Very recently, a trace gas sensor that detects a volatile impurity in dynamite has been marketed for civilian use in locating explosives.

Other applications of the chemical sensor concept under investigation by Army laboratories include trace gas detection of tunnels, personnel, military explosives, mines, and narcotics during search-type operations. Research in progress ranges from studies on the nature of specific trace gas signatures to development of new detector concepts which will meet requirements of ultrahigh sensitivity and selectivity. In these cases the concentration of signature chemical emitted at the source approaches the limit of sensitivity of modern analytical instrumentation. Dilution of the chemicals in air reduces even further the concentration to levels quite low with respect to background atmospheric trace contaminants that can act as interferences. Although results of research and development in this area are quite encouraging, considerable effort may be required before relevant technology can be advanced to the point where practical trace gas detection systems can be demonstrated in the above applications.

Experience in these areas indicates that the development of chemical sensors remotely placed for vehicle surveillance appears more immediately promising. In this case sensors would be employed in a fixed position to monitor anticipated routes of vehicle travel, this is an advantage over search-type operations. The exhaust of any vehicle contains various constituents present at much higher levels than normally encountered in the ambient atmosphere. The sensing of any individual component could provide a basis for vehicle detection, while variation in the exhaust composition of different vehicles is potentially useful for classification purposes. Because of the low concentration of exhaust chemicals in the ambient atmosphere, there should be a low false-alarm rate.

Possibly the past presence of vehicles could be evaluated by determining residual exhaust chemicals. Recent interest in development of air quality instruments for monitoring exhaust pollutants should have significant impact on technology applicable to sensor development for vehicle surveillance. In comparison with certain other sensor concepts, chemical sensors would not have disadvantages associated with requirements for maintaining an interface with the ground. Possibly the combination of chemical sensors with other types of detectors could enhance detection reliability or target classification capabilities.

The purpose of this study was to evaluate the potential for using chemical sensors for remote surveillance of vehicles for Remotely Monitored Battlefield Sensor System (REMBASS). Specific

objectives included. 1) determine the feasibility of vehicle detection/classification; 2) evaluate concepts suitable for use in development of chemical sensors; and 3) recommend performance characteristics and physical properties, and develop criteria for selected chemical sensor concepts.

To accomplish these objectives within the time frame available, the program was conducted jointly by the U.S. Army Cold Regions Research and Engineering Laboratory, Edgewood Arsenal and the U.S. Army Tank Automotive Command. Participation of each laboratory in the various aspects of the program was defined as follows.

USA CRREL: 1) Coordinate the overall program, 2) determine the feasibility of military vehicle detection, 3) determine the feasibility of military vehicle classification, 4) publish a jointly prepared final report.

EDGEWOOD ARSENAL: 1) Evaluate existing chemical sensor concepts for application to REMBASS, 2) evaluate performance of existing sensors such as the condensation nuclei detector and the Honeywell ionization detector (Air Force Multiagent Detector).

USATACOM: 1) Arrange for field test sites and a cross section of military vehicles; 2) provide necessary support in conducting field tests, 3) determine characteristics of military vehicles and other sensor concepts.

This report contains the collective input of the participating laboratories.

SUMMARY AND RECOMMENDATIONS

A study was conducted to evaluate the concept of using remotely placed chemical sensors for vehicle surveillance. The validity of this approach for vehicle detection was demonstrated during field trials. Results of field and laboratory studies indicate that classification of gasoline and diesel vehicles based on differences in exhaust composition should be feasible. A number of chemical sensor concepts were found to have potential for development as vehicle detectors or classifiers.

Field tests were held at Yuma, Arizona and at Warren and Grayling, Michigan, to provide a range in environmental conditions for evaluating the concept of using chemical sensors for vehicle surveillance. Detectability of a variety of gasoline and diesel powered military vehicles was determined at each site by continuously monitoring several major exhaust components including combustion particulates, nitrogen oxides, hydrocarbons, sulfur compounds, and carbon monoxide. Detection of particulate matter and nitrogen oxides from all types of vehicles was highly successful at downwind ranges up to 390 m and 150 m respectively. Longer downwind ranges could be obtained with lower detection probability. Detection of sulfur primarily from diesel vehicles, and hydrocarbons from gasoline vehicles was obtained at downwind ranges up to 35 m, although longer ranges should be possible. Based on these results, it is felt that the feasibility of detecting vehicles by sensing exhaust chemicals should be accepted as proven. Limited data were obtained in wooded terrain on the use of detectors placed on both sides of the vehicle path of travel to avoid dependence on wind direction. Although the range of detector placement was limited to 18 m because of the test situation, detection reliability was found to be 100% after a large number of trials. No false signals were observed during field tests in remote locations. Although signals due to pollution sources were present during tests at Warren, the characteristics of the response of chemical monitors to pollutant sources were considerably different from those of the response to vehicles. Vehicle detection was possible when monitoring a roadway downwind from a heavily traveled road.

In exploring possibilities for vehicle classification, a laboratory study was conducted to determine the molecular composition of the organic fraction of military vehicle exhausts. Generally, no significant differences were noted in the limited number of exhaust samples collected from only gasoline vehicles, or in exhaust samples collected from only diesel vehicles; however, the characteristics of the organic emissions from these two classes of vehicles were sufficiently different to provide a basis for classification. This would permit the distinction between light- and heavy-weight military vehicle traffic, or possibly, between civilian and military traffic.

Another approach to the same level of classification is based on differences in the composition of major exhaust components. Available evidence from field tests and other sources suggests that particulate matter, nitrogen oxides, and carbon dioxide should be indicative of both gasoline and diesel vehicles. Sulfur compounds would favor the presence of a diesel vehicle, while hydrocarbons and carbon monoxide should be indicative of the presence of gasoline vehicles. By combining two simple detectors to form a classifier unit, it should be possible either directly or deductively to distinguish between diesel and gasoline vehicles.

Trade-off analysis of chemical sensor concepts that appeared most applicable to the detection of vehicles by remotely placed sensors indicated that condensation nuclei, surface adsorption, and Honeywell ionization detectors ranked in decreasing order. Chemical classifiers were configured from pairs of chemical sensors which in order of preference included the dual Honeywell ionization system, the condensation nuclei/Honeywell ionization classifier, the dual surface adsorption classifier, and the condensation nuclei/surface adsorption classifier.

Before considering other possible alternatives, the above concepts should be evaluated in detail. However, it is not necessary to study each approach individually since only three types of sensors are recommended. The characteristics of the condensation nuclei detector are fairly well established, so in this case a feasibility study is not critical except for exploring the possibility of operating below freezing temperatures. However, an in-depth evaluation should be made to determine whether the Honeywell ionization and surface adsorption sensors can be optimized to respond as required to individual exhaust components. Once this information is available, the use of these sensors alone, or combined with each other or other sensors, can be objectively evaluated.

Although other types of sensor concepts such as seismic, acoustic, magnetic, electromagnetic, thermal imagery, and electro-optical techniques could not be considered within the scope of this study, USATACOM has collected signature data for a variety of vehicles, using some of these sensors, while conducting work for the Defense Special Projects Group. This experience has shown the necessity of developing a variety of sensor devices since each technique has characteristics that limit its usefulness depending on target type, and environmental and tactical situations.

The general advantages of chemical sensors appear to be low false-alarm rate and a lack of susceptibility to problems resulting from the requirement of some other sensors for ground interfacing. Chemical sensors seem equal or superior to other sensors in terms of detection range for vehicles. A combination of two chemical sensors appears useful for limited vehicle classifications. Chemical sensors would normally respond only to vehicles, this is a certain level of classification.

Chemical sensors also have disadvantages. Although their unit costs may ultimately be competitive in many cases, development costs to reach the state of the art of other sensor devices are higher because of a lack of previous development support. (It is estimated that over 1.6 billion dollars have been expended through 1971 on nonchemical intrusion detection systems.) Chemical sensors are generally more complex than other sensor types and generally have high power requirements on the order of several watts which would limit the period of unattended use. The response of chemical sensors is highly dependent on wind conditions although evidence indicates that the downwind placement requirement can be overcome by proper placement of two detectors. Even

for other types of detectors, proper placement is essential to provide an acceptable level of detection at a low false-alarm rate. For chemical sensors, response can essentially be in real time after acquisition of exhaust vapors, however, effective response time varies with factors such as wind speed and range which determine the period of movement of exhaust vapor from the vehicle to detector site.

No serious consideration has been given to the possibility of using chemical sensors and other types of sensors in combination to improve surveillance capabilities. However, it seems probable that the combination of chemical sensors with other sensors could permit personnel-versus-vehicle classification with a high degree of reliability. The use of other sensors to trigger chemical sensors could provide complementary information while reducing the power requirement of the chemical unit. While this study has considered the use of chemical sensors only for vehicle surveillance primarily along roads, other applications include conducting bridge security operations, monitoring waterways for boat traffic, and surveillance of remote airfields. Specific recommendations based on this study are:

1. The condensation nuclei detector should be considered for immediate inclusion in the REMBASS system.

2 Studies should be supported to extend the operational capability of the condensation nuclei detector for operation in cold regions.

3. Because of the advantages in size, weight, and unit cost of the surface adsorption detector, a continuing program should be supported to develop adequate sensitivity and performance for REMBASS application.

4. Feasibility studies to fully exploit the potential of the Honeywell ionization detector for REMBASS applications should be supported.

5. A limited study should be supported to determine optimum deployment requirements for any chemical sensor system in a variety of tactical environments.

6. A study should be conducted to evaluate the combination of chemical sensors with other sensor systems for application in the REMBASS program.

A vehicle exhaust gas signature program should be conducted to provide a base line for future vehicle classification systems.

MILITARY VEHICLE CHARACTERISTICS

The detectability of exhaust gas components is influenced by vehicle-related characteristics which determine total exhaust volume and composition. The more obvious of these characteristics are engine type, fuel type and grade, and operating conditions. These variables probably have an even more significant impact on the possibility of classification of vehicles by exhaust analysis. Consequently, an attempt was made during field tests to gain experience with a range in types of military vehicles.

The characteristics of engines of common U.S. Army vehicles ranging from the ¼-ton utility truck to the main battle tank are shown in Table I. Some of these vehicles, while no longer employed by the Army, are currently used by National Guard units. Many of the vehicles are in the arsenals of friendly nations. Unfortunately, it was not possible to schedule tests of foreign military vehicles. However, Soviet Bloc vehicles that correspond to U.S. vehicles are identified in Table I[1] for comparison. Engine characteristics of the Soviet vehicles are also summarized in Table I. Currently the larger logistical vehicles and the armored tactical vehicles of both U.S. and Soviet equipment

[1] USAREUR PAM 30-60-1, Identification handbook, Soviet and satellite ordnance equipment, sixth revised edition.

Table I. Engine characteristics of military vehicles.

U.S. vehicles

Vehicle	Type	Cyl	Cu in. disp	HP	Comp ratio	Cooling	Fuel	Comparable Soviet
M151	¼ ton	4	141.5	71	7.5:1	liquid	gasoline	UAZ69
M38A1	¼ ton	4	134	72	6.9:1	liquid	gasoline	UAZ69
M715	1¼ ton	6	230.5	132.5	7.5:1	liquid	gasoline	GAZ66
M35A2	2½ ton	6	427	140	20:1	liquid	diesel	ZIL157
M809	5 ton	6	855	250	15.5:1	liquid	diesel	
M123A1	10 ton	8	785	300	16.9:1	liquid	diesel	KRAZ255B
M113	APC	8	361	194	7.8:1	liquid	gasoline	BTR50P
M113A1	APC	6	318	202	21.5:1	liquid	diesel	BTR50P
M551	tank	6	318	300	17:1	liquid	diesel	
M48A1	tank	12	1792	810	6.5:1	air	gasoline	T54
M60A1	tank	12	1791	750	16:1	air	diesel	T55

Soviet Bloc vehicles

Vehicle	Type	Cyl	Cu in. disp	HP	Comp ratio	Cooling	Fuel	Comparable U.S.
UAZ69	½ ton	4	149	70	6.6:1	water	gasoline	M151
GAZ66	1¼ ton	8	259	110	6.8:1	water	gasoline	M715
ZIL157	2½ ton	6	339	109	6.2:1	water	gasoline	M35A2
KRAZ255B	10 ton	8	908	240	16.5:1	water	diesel	M123
BTR50P	APC	6	1166	237	15:1	water	diesel	M113A1
T55	tank	12	2367	572	14.5:1	water	diesel	M60A1

are diesel powered, while the lighter utility vehicles are gasoline powered. Compression ratios of the Soviet vehicles tend to be lower than those of the U.S. counterparts, possibly providing some basis for expecting chemical signature differences. In addition, the Soviet battle tank, the T55, is liquid cooled, while the U.S. M60A1 battle tank is air cooled. This may result in a variation in engine operating temperature which could be reflected by a difference in chemical signature.

The amount of exhaust gas emitted by each vehicle is determined by both the displacement of its engine and the engine speed at which the vehicle operates. For example, the M60A1 tank with a turbo-charged 1791-in.^{3} displacement engine expels approximately 175 lb of exhaust/min when traveling 30 mph. Other vehicle engines would expel considerably less exhaust if they were naturally aspired, had smaller displacement, or were run at lower speed.

In consideration of what is in store for military vehicles over the next 15-year period, the same general types of vehicles and power plants that are currently in the military vehicle arsenal will probably continue in usage. For ¼-ton and 1¼-ton infantry support vehicles, gasoline will continue to be used as fuel in conventional engines. For 2½-ton and larger vehicles diesel power will be employed. Engine types such as the turbine and rotary piston, while under research and development for potential military application, are not currently in use in any standard issue vehicles. In the 1985 to 1990 time frame, some turbine powered vehicles may be developed, particularly for high-mobility combat missions.

There are three types of U.S. military diesel fuels for regular, winter, and arctic use.[2] The regular (DF2) and winter (DF1) grades contain no more than 0.5% sulfur, whereas the arctic grade (DFA) sulfur content is limited to 0.15%. The winter and arctic grades have increasingly lower viscosities, reflecting a higher percentage of lighter weight hydrocarbons. [The sulfur content of Soviet diesel fuel ranges from 0.4% for arctic grade (A) to 1% for regular grade (L).[3]] There are two grades of gasoline for all-purpose (Type I) and low-temperature (Type II) use.[4] Both grades are limited to 0.15% sulfur. Fuels contain various additives such as oxidation and corrosion inhibitors, metal deactivators, and antiknock compounds which may be of consequence in vehicle detection and classification. In this regard consideration should be given to tagging U.S. fuels with additives which are identifiable in exhaust for detection purposes.

Values of the typical concentration of prominent exhaust constituents from both diesel and gasoline engines are shown in Table II. These values were obtained by infrared analysis of exhaust gases. It is emphasized that these values can vary over a wide range. Also, the total amounts of exhaust emitted into the atmosphere vary with engine physical and operating characteristics. The concentrations of nitrogen oxides and carbon dioxide appear comparable for both diesel and gasoline engines. Gasoline engine exhaust may contain more carbon monoxide, hydrogen, and hydrocarbons, while diesel engine exhaust contains more sulfur. All exhausts contain large numbers of combustion product particulates. These differences indicate potential for classification of diesel and gasoline vehicles; however, the exact significance in terms of detection or classification is difficult to judge without field test data because of the number of interacting factors which influence exhaust composition downwind from the vehicles. Detailed analysis of the hydrocarbon fraction may be useful for classifications of the various types of diesel and gasoline powered vehicles.

The vehicles included in the field tests at Yuma, Arizona, and Warren and Grayling, Michigan, to be discussed later are indicated in Table III. The exhaust from a number of these vehicles was sampled for detailed molecular analysis in the laboratory to determine if differences in exhaust organic compounds might be useful for classification. The vehicles tests are illustrated in the photos shown in Figures 1-9. The M151 ¼-ton logistic carrier (Fig. 1) has replaced the M38A1. The M715 1¼-ton utility truck (Fig. 2) is the current issue replacement for ¾-ton vehicles. The M35A2 2½-ton truck (Fig. 3) is the current high density vehicle. The M809 (Fig. 4) and M123A1 (Fig. 5) are 5-ton and 10-ton tractors. The diesel M113A1 armored personnel carrier (Fig. 6) has replaced the gasoline powered M113. The current high-mobility tank is the M551 (Fig. 7). The M48A1 gasoline powered main battle tank (Fig. 8) has been replaced by the M60A1 (Fig. 9), which is diesel powered with exhaust gas mixed with cooling air.

Table II. Chemical composition of exhaust from diesel and gasoline engines.

Constituent	Typical concentration (%) Diesel	Gasoline
Carbon dioxide	9.0	9.0
Carbon monoxide	0.1	4.0
Hydrogen	0.03	2.0
Hydrocarbons	0.02	0.5
Nitrogen oxides	0.04	0.06
Sulphur dioxide	0.02	0.006

[2] Federal Specification VV-F-800a (1968) Fuel oil, diesel. 22 May.
[3] Soviet Specification ST-CS-04-20-71 (1971) 27 Jan.
[4] Military Specification MIL-G-3056C (1967) Gasoline, automotive, combat. 31 Aug.

Table III. Military vehicles included in field studies.

Vehicle	Size			Exhaust sampled for molecular analysis
	Yuma	Warren	Grayling	
M151A1	G	G	G	X
M715	G	G	G	X
M113			G	
M113A1	D			X
M809		D	D	
M123A1	D		D	X
M35A2	D	D	D	X
M551	D			X
M48A1			G	
M60A1	D			X

G = gasoline; D = diesel

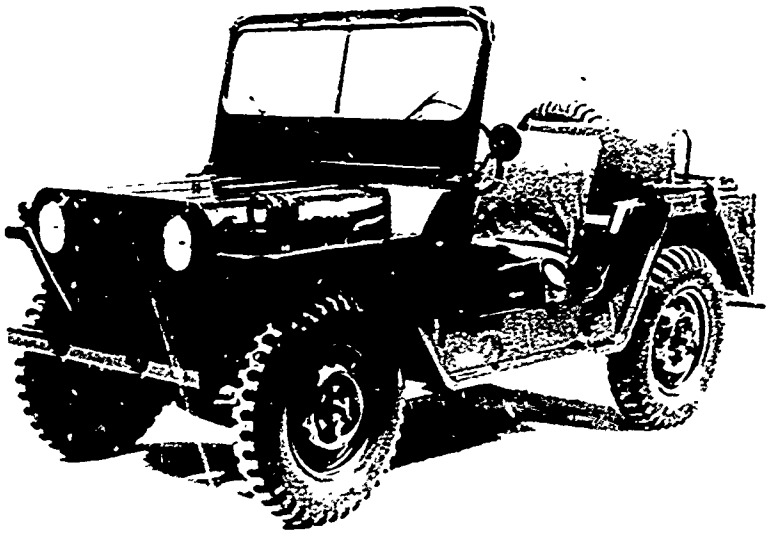

Figure 1. U.S. ¼-ton vehicle, M151.

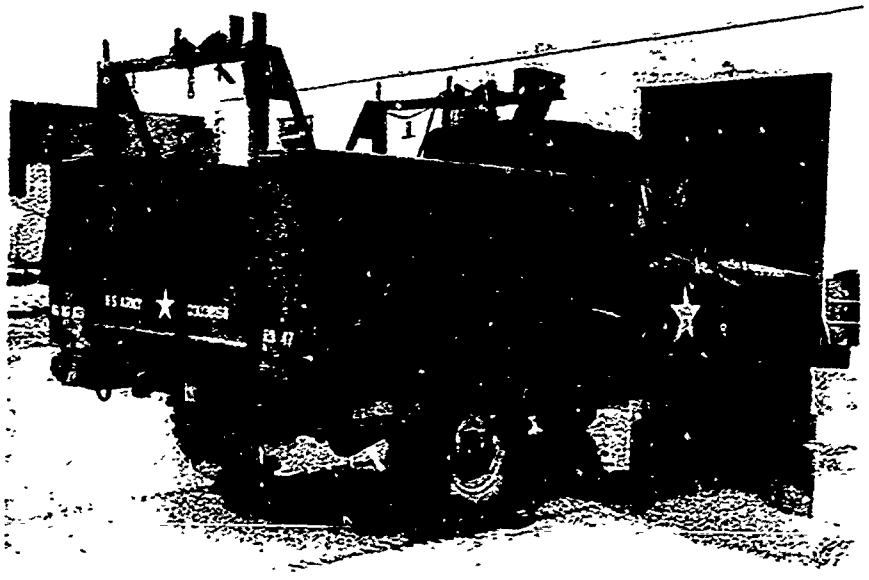

Figure 2. U.S. 1¼-ton truck, M715.

Figure 3. U.S. 2½-ton truck, M35A2.

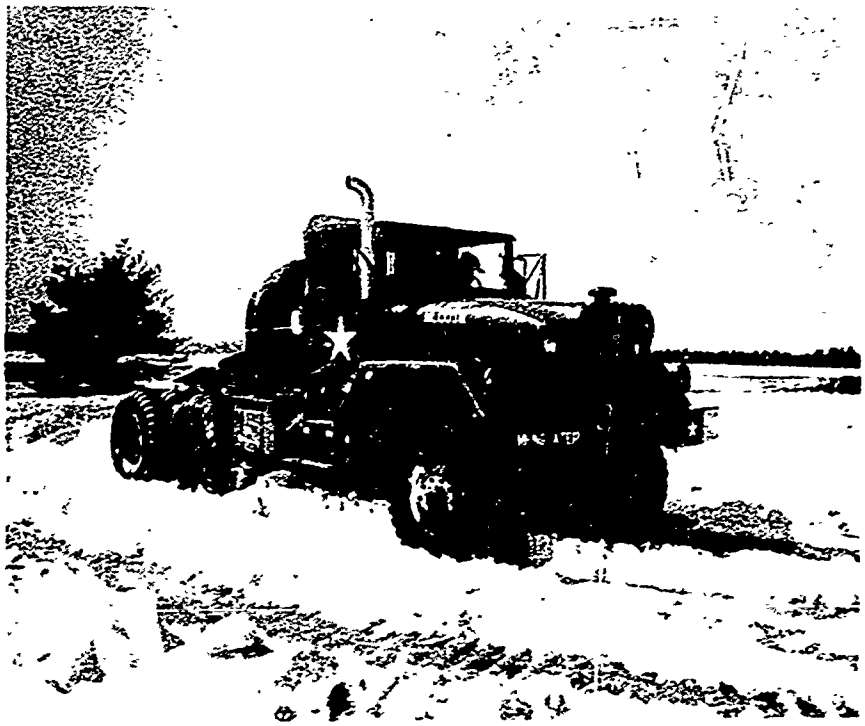

Figure 4. U.S. 5-ton truck, M809.

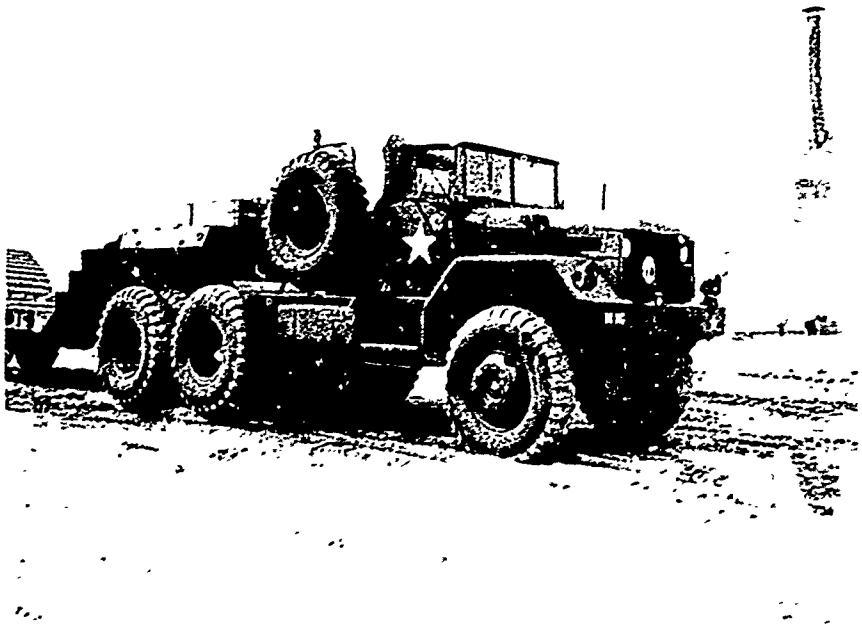

Figure 5. U.S. 10-ton truck, M123A1.

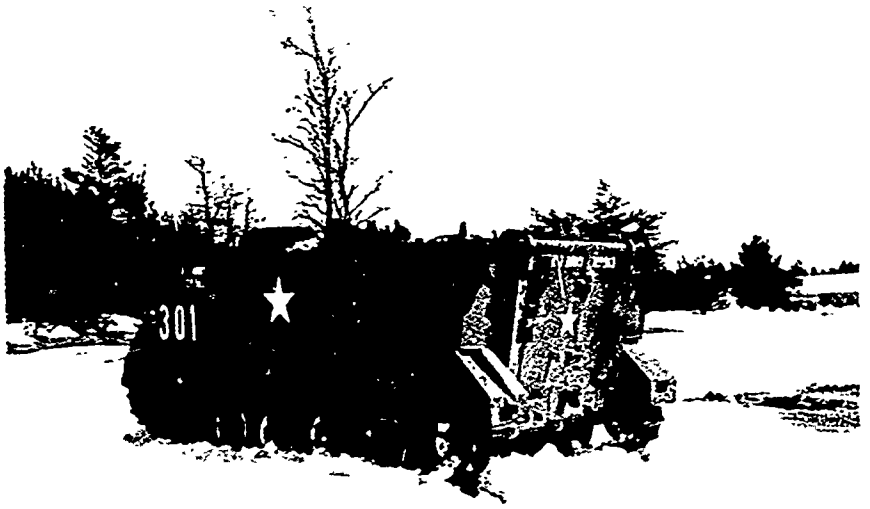

Figure 6. U.S. APC, M113 and M113A1.

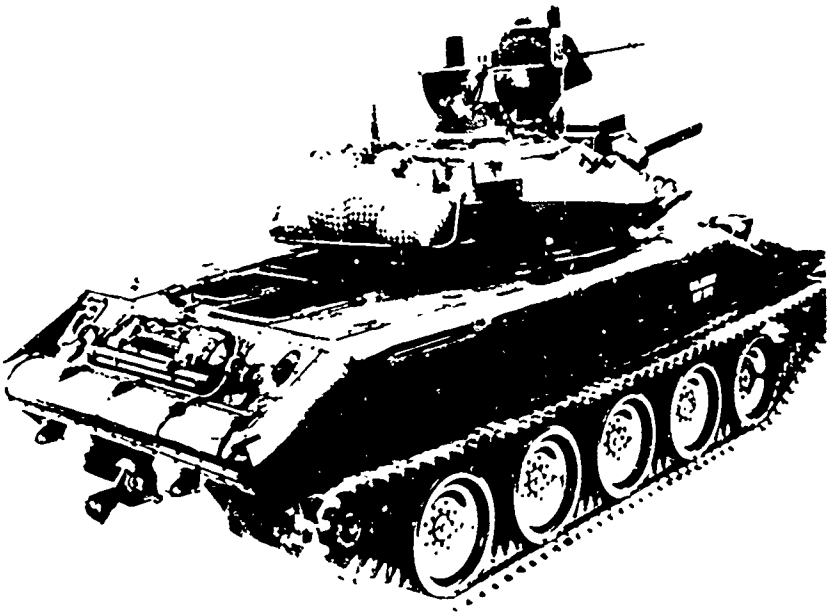

Figure 7. U.S. tank, M551.

Figure 8. U.S. tank, M48A1.

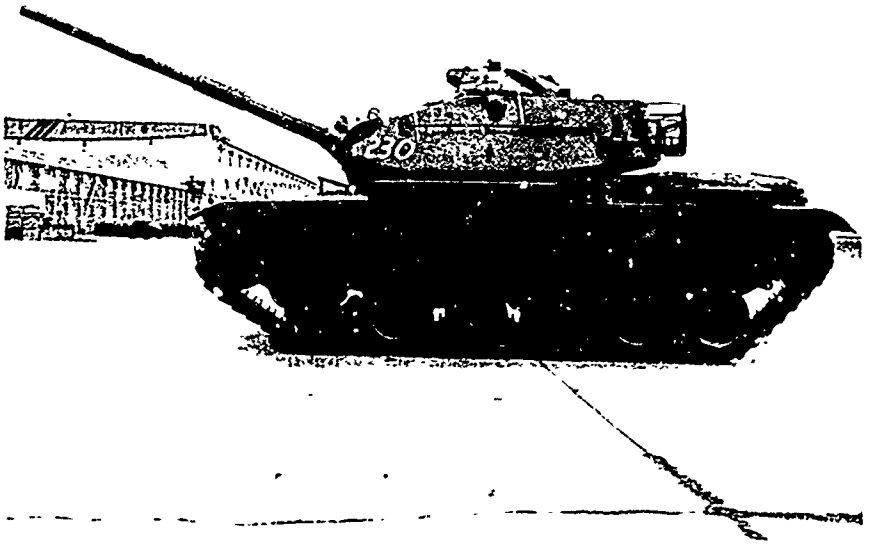

Figure 9. U.S. tank, M60A1.

In conducting field tests no attempts were made to tune the vehicles to maximum operating performance. They were run "as received," which is indicative of their condition under normal field operation as supported by organizational and direct support level maintenance. No attempt was made to obtain the newest vehicle available in each class. Consequently, most of the vehicles had accumulated a considerable number of miles prior to the field tests. All vehicles were standard issue with regard to engine and power train. However, in some cases minor modifications had been made to other portions of the vehicle which were not related to operating parameters. DF2 diesel fuel and Type-I gasoline were used during all tests.

FEASIBILITY OF VEHICLE DETECTION

In order to evaluate the concept of military vehicle detection using chemical sensors, the detectability of various exhaust components from vehicles operating under field conditions was determined using state-of-the-art chemical monitoring equipment. The principal objective of these field trials was to answer the following questions:

1. Is the concept of chemical detection of military vehicles valid?
2. What detection range is probable?
3. To what extent do local environmental conditions affect detection capability?
4. What kind of false-alarm frequency can be expected under various environmental conditions?
5. Do background concentrations in ambient air of the chemical components present in engine exhaust vary significantly?

Field tests designed to explore these questions were conducted at three locations. Yuma, Arizona, Warren, Michigan, and Camp Grayling, Michigan. These sites were chosen to provide a variety of environmental and terrain characteristics while taking advantage of locations with a ready supply of military vehicles available for testing. The Yuma and Camp Grayling sites had the added advantage of electric power availability in relatively remote locations, allowing vehicle testing without the complication of background vehicle traffic or pollution sources.

The types of chemical monitoring equipment used during field tests were selected to meet several criteria. First, the equipment was specific to at least one of the major exhaust components listed in Table II. The equipment had real time response characteristics (.2 sec), and as high a sensitivity as is currently available. Six types of chemical monitors were included in the field studies. A condensation nuclei monitor was chosen for detection of particulates because of its lack of response to dust particles as well as its high sensitivity to vehicle exhaust. A chemiluminescence monitor was included because of its sensitivity to nitrogen oxides which are prominent exhaust components but which are found at very low levels in ambient air. Although the amounts of sulfur compounds present in exhaust are small compared with some other exhaust components, the flame photometric monitor has an inherent sensitivity several orders of magnitude higher than most instruments and hence was also included. A flame ionization hydrocarbon analyzer was chosen because of its combined response to both hydrocarbon and aldehyde fractions of exhaust as well as its relatively high sensitivity. An infrared absorption analyzer sensitive to carbon monoxide was another choice. The low levels of carbon monoxide in unpolluted air as compared with the concentrations found in engine exhaust made it a likely candidate. The sixth system chosen for field study was the Honeywell ionization detector or the Air Force Multiagent Detector. This system, although at present optimized for chemical agent detection, was generally configured for field use and had the potential advantage for modification to sense several different exhaust components.

Detection equipment sensitive to carbon dioxide was considered but not included because of the high level of carbon dioxide present in ambient air. A hydrogen detector was not considered since the presence of hydrogen gas as a component of engine exhaust was not realized initially and suitable equipment was not readily available.

It should be emphasized that the major objective of these tests was to evaluate the detectability of the individual exhaust components under field conditions. Field configured chemical detectors were concurrently evaluated when available; however, these were limited to the condensation nuclei detector, and the Honeywell ionization detector. The other instruments used do not necessarily represent the types of equipment best suited for detector development, but rather represent current state-of-the-art laboratory air monitoring devices.

Field Studies

Yuma, Arizona

The first field test was held 1-10 February 1972 at the Yuma Proving Ground, Yuma, Arizona. Because this was the first exercise, the main objective was to determine the general feasibility of detecting military vehicles operating under field conditions using chemical detectors. We also hoped to determine the detection range in open terrain as well as the effect of wind speed and direction on detection capability. Background levels of the various chemicals found in exhaust were also monitored as they related to the false-alarm rate that might be expected using chemical sensors, and to the practical lower limit of sensitivity for detector design.

The terrain at Yuma is gently rolling with very little ground cover, as can be seen in Figure 10. The ambient temperature during this time of year ranges from the low 40's to the middle 60's (°F). The site chosen was located in a remote section of the Yuma Proving Ground known as the chemical test area. The monitors were placed to sample air 3 to 4 ft from the ground. The test area (Fig. 11) was arranged to allow vehicle traffic to be monitored at various distances upwind from the sampling station. Two portable condensation nuclei detectors were arranged 100 and 200 m further downward sampling at ground level to gain as much information on detection range as possible from each vehicle pass. During the course of the test, some trials were made with the portable condensation nuclei detectors placed upwind of the vehicle path of travel to determine upwind detection capability.

The results of the Yuma test were generally quite good considering this was the first such attempt at vehicle detection. Military vehicles were shown to be detectable using chemical instrumentation. Data for individual types of vehicles are not shown. Rather, data were combined according to diesel or gasoline class. The condensation nuclei detector was clearly the most sensitive type of instrument used and results using this detector at various downwind ranges are summarized in Table IV. The condensation nuclei monitor was highly sensitive to all types of vehicles up to 400 m in open terrain. At greater distances, more success was found in detecting the larger diesel powered vehicles than the light-duty gasoline powered ones. The response characteristics of this detector at several downwind distances are shown in Figure 12. The magnitude of detector response of two 400-yd detections differed from that of two 500-yd detections (trials 2 and 3). This was caused by variations in the meteorology and the fact that the truck was traveling in different directions for the two trials. In one trial, the exhaust pipe was pointing towards the detectors and was not affected by the turbulence created by the truck. In the other trial, the exhaust pipe was pointed away from the detectors and the exhaust passed through the turbulence before it could reach the detectors. In one trial, the exhaust cloud was dispersed, resulting in a longer time of exposure to the detector. In the other situation, the exhaust cloud was narrow and passed by the detector more rapidly. This influence of exhaust pipe location on detector response characteristics was observed for many types of vehicles.

Figure 10. Site characteristics, Yuma, Arizona.

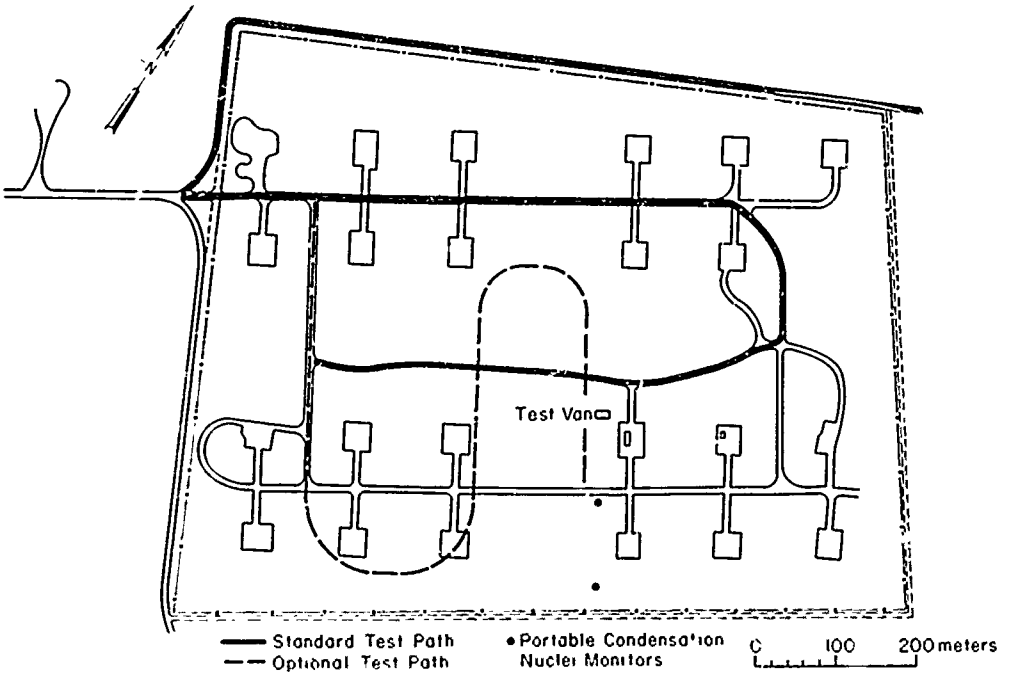

Figure 11. Test area, Yuma, Arizona.

Table IV. Detection of military vehicles at various downwind distances in open terrain using a condensation nuclei detector.

Range (m)	Vehicle type* Diesel Trials	Diesel Detections	Gasoline Trials	Gasoline Detections	Total Trials	Total Detections
18	12	12	10	10	22	22
35	29	29	10	10	39	39
135	21	20	11	9	32	29
235	18	16	11	9	29	25
290	15	14	5	3	20	17
400	23	21	12	5	35	26
500	19	14	12	2	31	16
600	6	4	6	1	12	5

*Data obtained for the various diesel vehicles and gasoline vehicles tested are combined under each heading.

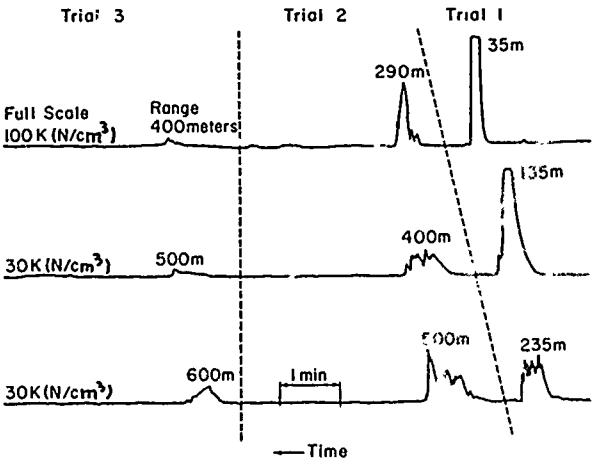

Figure 12. Typical responses of condensation nuclei detectors to M123 10-ton diesel truck operating in open terrain with 10-mph wind speed.

Some of the other chemical sensor systems also met with considerable success, their results are summarized in Table V. The Honeywell ionization detector and the chemiluminescence monitor were highly successful in detecting vehicles at the 18 and 35-m ranges. Their response characteristics as compared with those of the condensation nuclei detector are given in Figure 13. The flame photometric unit responded at ranges up to 35 m for diesel vehicles but was not sensitive at these ranges to gasoline powered ones. The flame ionization monitor was subject to operational problems during the tests but at times responded to gasoline powered vehicles. The infrared carbon monoxide monitor was inoperable during testing so results for this system are not given. In several cases detection at 35 m was better than at 18 m. This was generally the result for several types of vehicles whose exhausts were thrown high into the air and did not descend to ground level within the 18-m distance.

The detection data shown in Tables IV and V are conservative since changes in wind direction after initiation of a trial prevented detection in some cases. This was particularly true at larger ranges.

Table V. Detection of military vehicles at various downwind distances.

Sensor type	Range (m)	Vehicle type* Diesel Trials	Diesel Detections†	Gasoline Trials	Gasoline Detections†	Total Trials	Total Detections†
Open Terrain							
Condensation nuclei	18	12	12	10	10	22	22
(Combustion particulates)	35	29	29	10	10	39	39
	150	3	3	0	0	3	3
	290	15	14	5	3	20	17
	400	23	21	12	5	35	26
Chemiluminescence	18	14	10	8	8	22	18
(Nitrogen oxides)	35	23	22	6	6	29	28
	150	4	4	0	0	4	4
	290	14	10	6	0	20	10
	400	13	8	6	0	19	8
Honeywell ionization	18	9	8	16	15	25	23
(Unknown)	35	32	30	21	13	53	43
	290	18	7	8	1	26	8
	400	12	8	8	0	20	8
Flame photometric	18	14	5	10	2	24	7
(Sulfur)	35	23	18	10	0	23	18
	150	3	0	0	0	3	0
	290	15	0	6	0	21	0
	400	12	0	6	0	18	0
Flame ionization	18	17	0	10	3	27	3
(Hydrocarbons)	35	19	0	10	2	29	2
	150	1	0	0	0	1	0
	290	12	0	6	1	18	1
	400	8	0	6	1	14	1
Urban Environment							
Condensation nuclei	12	20	20	10**	6	30†	26
(Combustion particulates)	17	18	18	10	10	28	28
	27	25**	21	21**	19	46**	40
Chemiluminescence	12	20	18	10**	0	30**	18
(Nitrogen oxides)	17	18	18	10	9	28	27
	27	25**	21	21**	9	46**	30
Flame photometric	12	20	14	10**	0	30**	14
(Sulfur)	17	18	18	10	0	28	18
	27	23**	10	21**	0	44**	10
Flame ionization	12	20	2	10	7	30	9
(Hydrocarbons)	17	18	1	9	4	27	5
	27	25**	1	21**	3	46**	4

Table V (Cont'd).

Sensor type	Range (m)	Vehicle type * Diesel Trials	Diesel Detections†	Gasoline Trials	Gasoline Detections†	Total Trials	Total Detections†
		Wooded Terrain					
Condensation nuclei	27	16	16	50	46	66	62
(Combustion particulates)	88	6	6	11	9	17	15
Chemiluminescence	27	16	15	50	33	66	48
(Nitrogen oxides)	88	6	2	11	6	17	8
Honeywell ionization	27	41	19	40	11	81	30
(Unknown)	88	6	0	10	1	16	1
Flame photometric	27	16	2	50	0	66	2
(Sulfur)	88	6	0	11	0	17	0
Flame ionization	27	16	0	50	12	66	12
(Hydrocarbons)	88	6	0	11	0	17	0

*Data obtained for the various models of gasoline and diesel vehicles tested are combined under each heading.
†In some cases no detection was made because of shift in wind direction after beginning a trial.
**No chance of detection in some cases due to interference from local pollution sources.

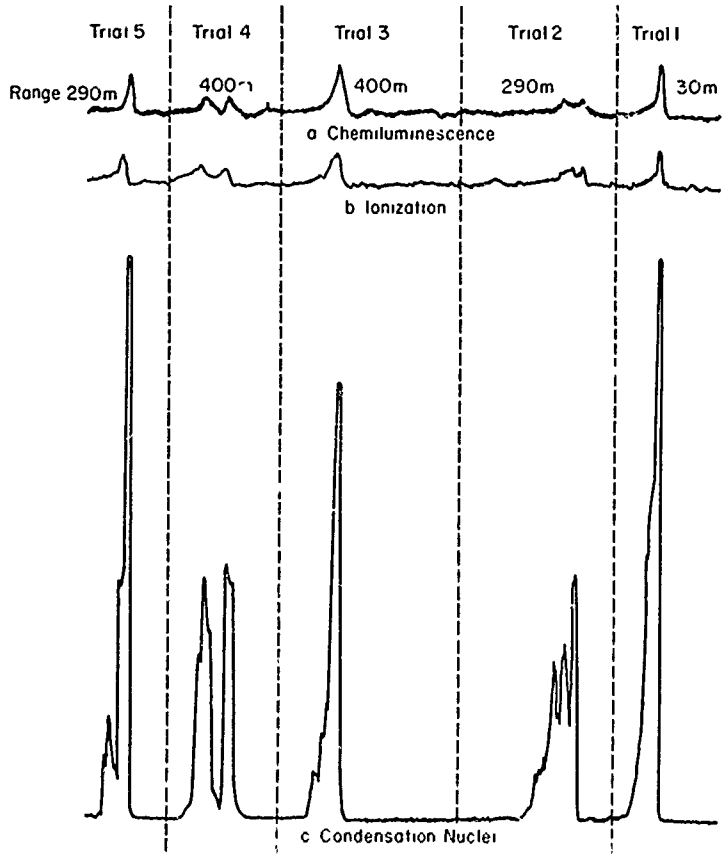

Figure 13. Comparison of responses from chemiluminescence monitor, and Honeywell ionization and condensation nuclei detectors in open terrain.

Wind conditions were an extremely important factor to detection capability. Wind speed during the test period varied considerably from about 15 to 20 mph on some days to a dead calm on others. Detection upwind of the vehicle path of travel was impractical even a few meters from the roadway. This indicates a requirement for at least two detectors, one placed on each side of the roadway, for successful vehicle detection in open terrain. Detection capability also suffered severely during zero wind conditions, where most of the exhaust tended to rise rather than diffuse laterally. High wind conditions did not seem to present particular difficulty but resulted in narrower peak widths in detector response characteristics, particularly at close range. Except under calm conditions, the exhaust tended to remain close to the ground and follow terrain features, indicating that detectors can be placed at ground level to minimize discovery by enemy forces.

By monitoring the chemical parameters on a 24-hour basis the false-alarm rate was shown to be zero. In all cases, an unexpected signal was attributable to other vehicles operating in the general vicinity of the test site. In fact, many times these vehicles were not observed until after a response was noted on the detection equipment.

Warren, Michigan

The second field test was scheduled for 5-11 April 1972 at USATACOM in Warren, Michigan. This site is located within metropolitan Detroit, where background levels of exhaust chemicals are expected to be considerably higher than those found at Yuma. The objective of this test was to determine the effect of high and variable background levels of exhaust chemicals on detection range using chemical instrumentation. The second objective was to investigate the false-alarm rate caused by operating near pollution sources. Finally, the third objective was to determine the possibility of using chemical monitoring equipment to observe a vehicle operating at close range downwind from a heavily traveled roadway.

The test site was located on the grounds at USATACOM (Fig. 14). The test procedure utilized existing roadways around the open area indicated as the test area in the illustration. Variable range was achieved by moving the equipment which was mounted in a mobile van. The Honeywell ionization detector was not available for this test, but the other monitors were the same as those used at Yuma. The temperature during the testing varied from 20°F to 50°F. Wind conditions were generally lighter and more variable than those found at Yuma and tests were run only when the chemical monitors were in a position to be downwind of the vehicle path.

Data from all vehicles were combined into diesel and gasoline classes. The results of the Warren test (Table V) indicate that the usable range of a chemical detector would be considerably less in an urban environment that that in a remote one. This is primarily due to the higher background levels of exhaust chemicals found in the urban atmosphere. False alarms were encountered when the monitoring system was directly downwind of a coal burning power plant located less than 300 m from the test site. The response to this type of false alarm was large but had a different peak shape and duration than that caused by a passing vehicle.

Experience during the tests at Warren showed that it is possible to detect a vehicle passing at close range, downwind from a heavily traveled road. The background traffic at a distance of a half mile or so caused an increased base-line level of exhaust chemicals but no distinguishable response peaks. The net effect would be a smaller effective detection range when operating under these conditions. The overall experience gained at Warren indicated that it is possible but considerably more difficult to engineer a chemical detector to operate in an urban environment than in a remote one.

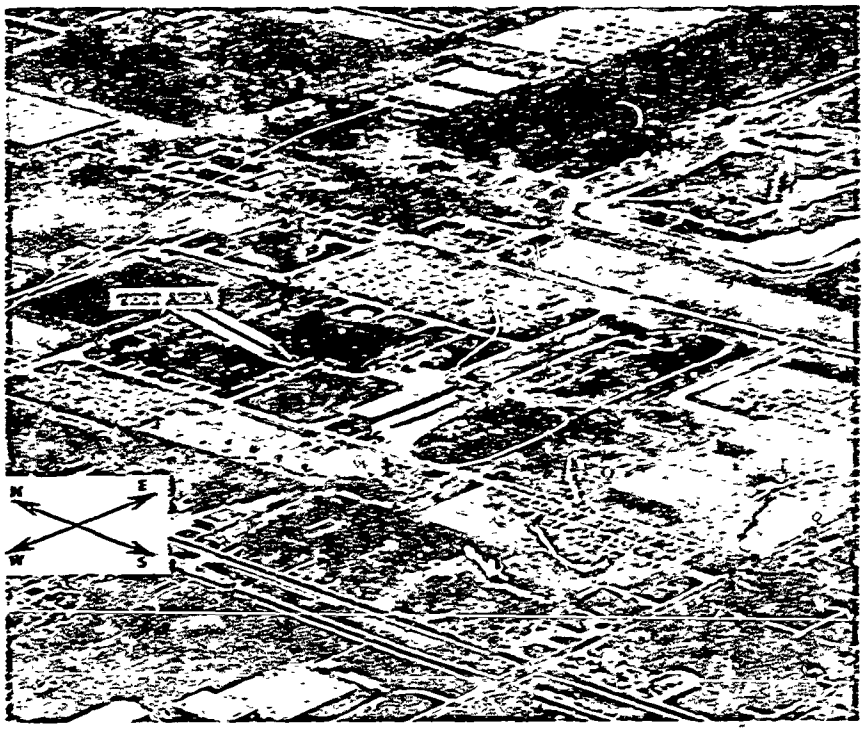

Figure 14. Site characteristics, Warren, Michigan.

Camp Grayling, Michigan

The third and final field trial was held 12-20 April 1972 at Camp Grayling, Michigan. The main objective of this test was to determine the effect of wooded terrain on detection range. The second objective was to explore any problems associated with operation on snow covered terrain. The third objective was to determine if proper placement of two detectors could give a high probability of detection independent of wind conditions.

The site chosen for this field test was located within a forested area of the camp, as shown in Figure 15. The ground had 1 to 2 ft of snow cover at the beginning of the test and temperatures ranged from 30 to 50°F. Wind conditions during the tests were generally light and variable. The test area is shown in Figure 16.

The chemical monitors and detectors used in this test were identical to those used at Yuma. Most of the equipment was mounted in two mobile vans located within the limits of the forest. Air was sampled 3 to 4 ft above the surface. The Honeywell ionization detector was placed slightly forward of van A and sampled at a height of 2 ft. Portable condensation nuclei detectors were deployed at 8 and 18 m respectively on either side of the main trail and sampled at ground level.

The results of the Camp Grayling test are given in Table V. The range of detection within a wooded area was more limited than that observed in open terrain. This is thought to be due to a more efficient dispersal of the exhaust cloud in a forest. Turbulence caused by air moving though the trees was probably responsible for this effect. No problems were observed in connection with operations under conditions of snow cover. Condensation nuclei monitors placed directly on snow operated properly, although ambient temperatures were generally above freezing.

Figure 15. Site characteristics, Camp Grayling, Michigan.

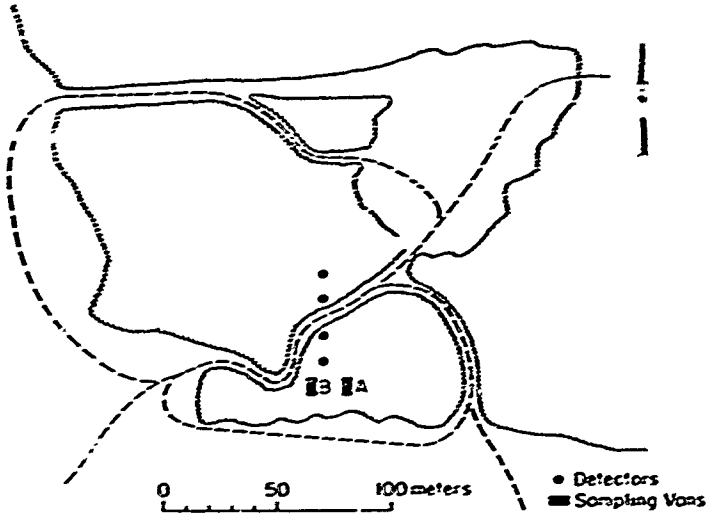

Figure 16. Test area, Camp Grayling, Michigan

In this test, as in others, the condensation nuclei monitor proved to be the most dependable detection system. The chemiluminescence monitor proved successful at the 27-m distance but did not perform well during passes at 88 m. The Honeywell ionization detector was operating at its range limits at 27 m and only one detection was made beyond. The flame ionization monitor again did not perform up to its capability but did occasionally respond to gasoline vehicles. The flame photometric monitor did not respond to gasoline vehicles at all and gave only two responses to the limited number of diesel vehicles available. The carbon monoxide monitor again did not operate properly during testing and results for it are not available.

A second study at Grayling involved the use of two detectors on both sides of the anticipated path of vehicle travel to circumvent the dependence of detection on wind direction. Portable condensation nuclei detectors were utilized for this study and were placed at distances of 8 m and 18 m on both sides of the trail. Approximately 100 trials were conducted using this detector configuration and in all cases a detector on at least one side of the road responded. Often detectors on both sides of the road responded indicating an upwind detection capability. The responses to several of these trials are shown in Figure 17.

Generally speaking, the heavy-duty vehicles tended to give larger responses than the light-duty ones but all vehicles were detected. Some limited testing was conducted to determine the range capabilities in this environment. Unfortunately, the test setup did not allow for deployment of detectors at extended ranges on both sides of the main trails. More distant trails were utilized to obtain some range data when wind conditions were favorable and some results of these trials are shown in Figure 18. Detections in this configuration were made up to distances of 72 m but the variability of the wind conditions limited meaningful analysis of range capabilities.

A small brush fire at a 10-m distance was used to simulate local interference. All of the monitoring equipment responded to the effluent from the fire. A fire at a greater distance is expected to raise the background level of particulates and combustion-type chemicals but would not prevent detection of vehicles operating at a shorter range.

Two surface adsorption detectors, sensitive to hydrocarbons and carbon monoxide, respectively, were given preliminary field tests at Camp Grayling. Consistent responses were noted at very close range, but only to gasoline powered vehicles. On one occasion, a response was obtained at a range of 27 m when a gasoline vehicle was started and moved out of the test area. It was determined that although this concept shows potential several modifications are required to obtain optimum response characteristics for field application.

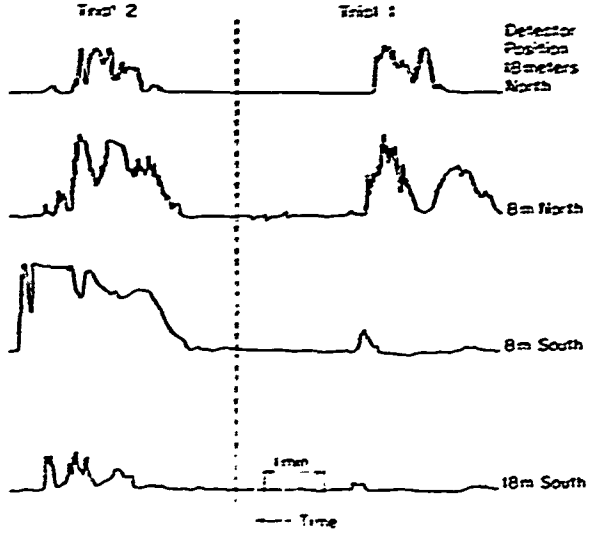

Figure 17. Typical response of condensation nuclei detectors located on both sides of vehicle path of travel in wooded terrain.

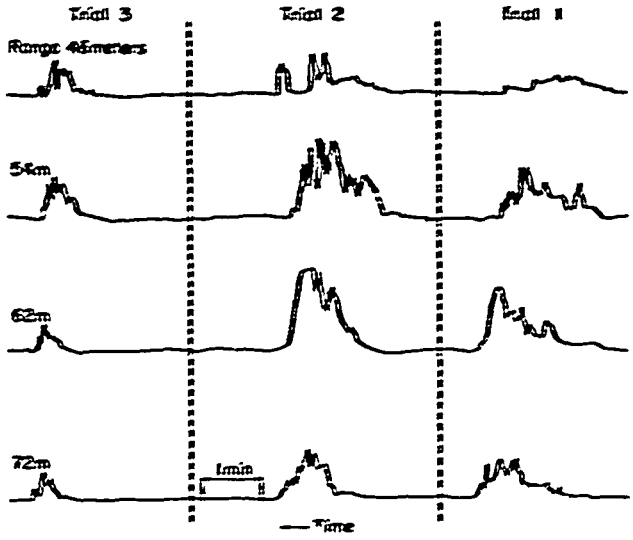

Figure 18. Typical response of condensation nuclei detectors arranged at different downwind distances in wooded terrain.

In conclusion, the effective detection range in wooded terrain seems to be somewhat less than that observed in open terrain. This is a judgment, since the test setup at Camp Grayling did not allow extensive range analysis. The probability of close-range detection, however, seems even higher in wooded than in the open terrain. The concept of placing two detectors on either side of a trail to be monitored seems to be an effective way to avoid dependence on wind direction. This concept is extremely important for practical use of chemical sensors. Further evaluation under a variety of terrain and environmental conditions to establish ranges that can be obtained independent of wind conditions is essential. The condensation nuclei detector was again the most successful sensor for both detection reliability and range. Placement of detectors near the ground proved successful in wooded terrain, which would again allow easy concealment. False alarms were not encountered during the Camp Grayling test.

Summary of Field Tests

The objective of the overall field test program was to evaluate the detectability of military vehicles operating under field conditions, using state-of-the-art chemical instrumentation. This was done in remote open terrain, an urban environment, and a remote wooded location. In all cases the vehicles proved to be highly detectable, as shown in Table VI.

Of the six types of sensors chosen for field study, the condensation nuclei detector was by far the most reliable detection system. In open terrain it had a detection range of up to 400 m, with a reduced detection probability at ranges up to 600 m. Although this range would be less in an urban or wooded environment, it would still be sufficient to ensure placement far enough from a roadway to avoid easy detection by enemy forces. The current M3 Personnel Detector is based on the condensation nuclei concept.

The other two systems that showed reasonable detection capability were the chemiluminescence monitor and the Honeywell ionization detector (Air Force Multiagent Detector). The chemiluminescence monitor was similar to the condensation nuclei detector in that it responded universally

Table VI. Summary of military vehicle detection using chemical sensors located downwind.

Sensor type	Range (m)	Vehicle type: Diesel Trials	Diesel Detections	Gasoline Trials	Gasoline Detections	Total Trials	Total Detections
Condensation nuclei	12 to 35	114	110	109	99	223	209
(Combustion particulates)	80 to 150	30	29	11	9	41	38
	150 to 300	32	23	16	14	48	42
	400 to 600	48	39	30	8	78	47
Chemiluminescence	12 to 35	116	104	105	65	221	169
(Nitrogen oxides)	80 to 150	10	6	11	9	21	15
	290	14	10	6	0	20	10
	400	13	8	6	0	19	8
Honeywell ionization	12 to 35	82	57	77	39	159	96
(Unknown)	80 to 150	6	0	10	1	16	1
	290	18	7	8	1	26	8
	400	12	8	8	0	20	8
Flame photometric	12 to 35	114	67	111	2	225	69
(Sulfur)	80 to 150	9	0	11	0	20	0
	290	15	0	6	0	21	0
	400	12	0	6	0	18	0
Flame ionization	12 to 35	115	4	110	41	225	45
(Hydrocarbons)	80 to 150	7	0	11	0	18	0
	290	12	0	6	1	18	1
	400	8	0	6	0	14	0

to all vehicles. The Honeywell ionization detector in its present configuration seemed to respond more to diesel powered vehicles but also detected gasoline vehicles. Both systems have a considerably shorter effective range in their present configuration than the condensation nuclei detector. The Honeywell ionization detector should be evaluated and modified if necessary for response to individual exhaust components before further field testing.

The flame photometric monitor responded at usable range only to diesel powered vehicles. The flame ionization monitor, on the other hand, was sensitive only to gasoline powered vehicles. Hence, neither system would be useful as a universal vehicle detector. The infrared monitor used for carbon monoxide detection did not prove successful during test runs when it was operational; this may have been due to the configuration of the particular monitor used. The preliminary tests run on the surface adsorption sensors were encouraging at short range. Modifications allowing optimization for use under field conditions are required before further testing can be conducted. In further tests, it would be worthwhile to include monitors for carbon dioxide and hydrogen.

Wind direction was determined to be an extremely important factor in vehicle detection capability. Upwind detection of vehicles proved to be impractical in open terrain, and limited in a forested environment. Tests run with detectors placed on both sides of the anticpated vehicle path, independent of wind direction, proved highly successful. More study is required to evaluate the generality of this approach. Study is also required to determine if this type of placement allows detection during a completely calm condition in open terrain

It was also determined that the exhaust cloud produced by a moving vehicle tended to remain near the ground in all locations tested. This allows detector placement at ground level, permitting easy concealment. The position of the exhaust pipe seemed to have a marked effect too. When the exhaust pipe pointed upwind of the vehicle, the vehicle's own turbulence seemed to spread the cloud, resulting in a broad response peak. When the pipe was pointing downwind, a much sharper peak resulted. This effect was noted repeatedly in all three locations tested.

Finally, the false-alarm rate determined in both remote locations was virtually zero. In the urban test, false alarms from close pollution sources were noted but these generally had different characteristics from detections resulting from a vehicle passing at close range.

FEASIBILITY OF VEHICLE CLASSIFICATION

Initial consideration of using chemical sensors to classify vehicle type indicated a high probability for differentiating between diesel and gasoline powered vehicles owing to differences in engine design, operating characteristics, and fuel composition. Since both domestic and foreign manufacturers currently use diesel engines exclusively in constructing medium- and heavy-weight military vehicles, and generally use gasoline engines in constructing light-weight commercial and military vehicles, it seemed desirable for intelligence purposes to be able to distinguish between these vehicle types. Furthermore, this level of classification seemed appropriate for an initial study of vehicle classification. A secondary objective was to determine if further classification within a vehicle class is possible.

Two approaches were taken. The first consisted of molecular analysis of the organic fraction of vehicle exhaust to determine if the types or concentrations of organic chemicals could be used for engine classification. The organic fraction was selected because of the large numbers of organic chemicals whose individual concentrations could be a function of engine size or type.

The second approach to classification was the analysis of data obtained during field monitoring of the major exhaust constituents, including total hydrocarbons, particulates, sulfur containing compounds and nitrogen oxides, to determine if one or a combination of these gross parameters could be used to distinguish between engine classes.

Molecular Analysis of Exhaust Organics

In the molecular analysis experiment, samples of exhaust gases from the various types of military vehicles indicated in Table III were taken at USATACOM and the Yuma Proving Ground. These samples were collected on a Porapak-Q collection tube similar in design to tubes currently being used in several laboratories[5] for collection and concentration of organic components for air samples. These samples as well as others taken for available vehicles at USA CRREL were analyzed on a combined gas chromatograph-mass spectrometer-data acquisition system. This method of analysis is considered to be the most powerful approach to separation and identification of complex mixtures of volatile organic chemicals currently available.

The results of this preliminary work indicate from a comparison of vehicles within an engine class that there is some variation in total quantity of exhaust organics, but similar relative composition. Comparison of diesel exhaust with gasoline exhaust, however, shows strikingly different

[5] Leggett, D.C., R.P. Murrmann, T.J. Jenkins and R. Barriera (1972) A method for concentrating and determining trace organic compounds in the atmosphere. USA CRREL Special Report 176.

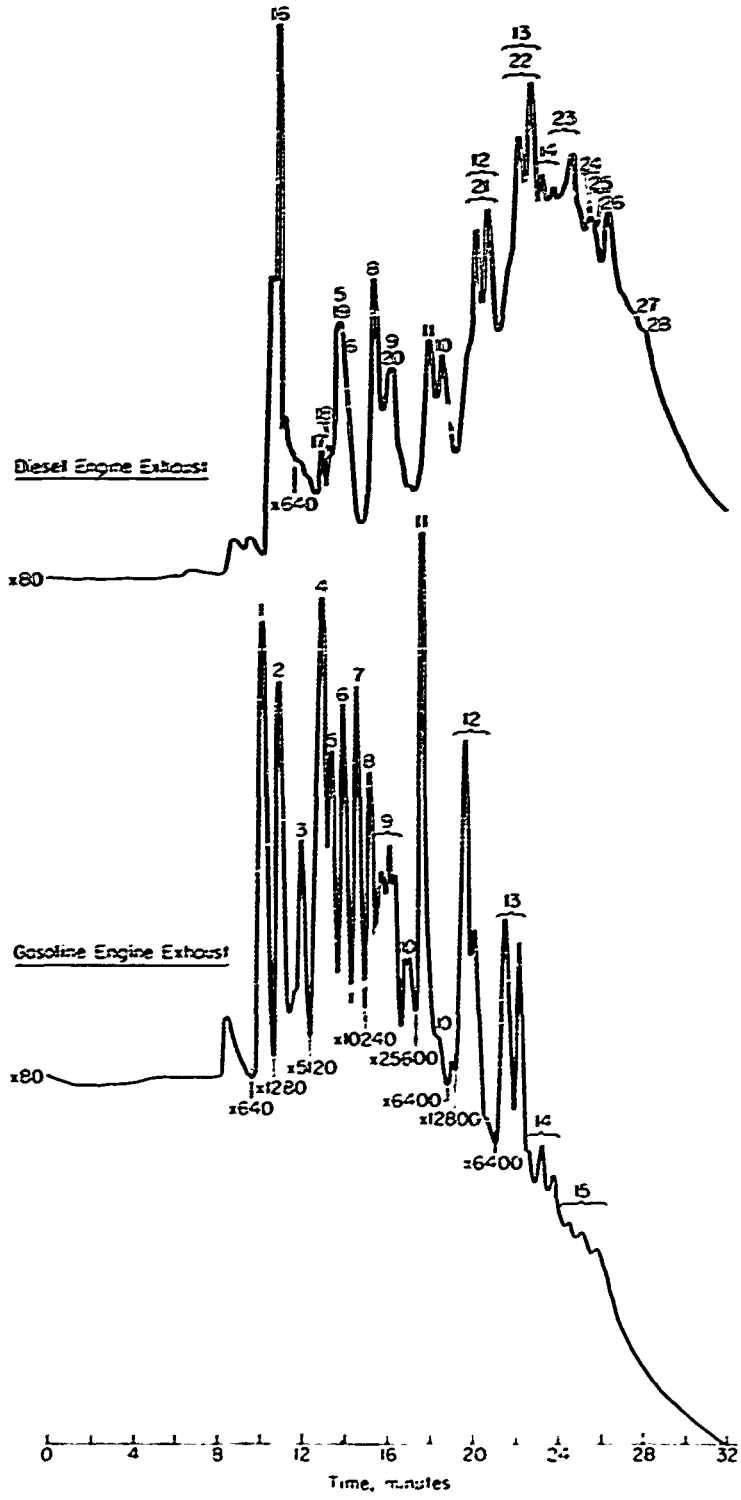

Figure 19. Typical chromatograms of organic fraction of vehicle exhaust collected under field conditions.

relative composition as well as a large variation in total organic content. Analysis of the data indicates that the major components of the organic fraction of exhaust from both engine types consist of the following chemical types (lead-containing organic chemicals in gasoline exhaust have not been considered because of their ease of elimination by changing to lead-free gasoline): 1) saturated, unsaturated and aromatic hydrocarbons; 2) oxygenated compounds; 3) aliphatic nitro compounds; and 4) some sulfur containing species. Since it was impossible to separate and identify each of the many individual chemicals present, emphasis was placed upon identification of the most prominent species relevant to discrimination between the two engine types.

The gasoline engine emitted volatile organic chemicals in significantly larger concentrations than the diesel engine. Of these compounds, the molecular weight distributions of the saturated hydrocarbon fraction from the two types of exhaust were substantially different, and paralleled the difference in fuel composition. In particular, the gasoline engines emitted large amounts of saturated hydrocarbons in the range C_5 to C_8, while these compounds in diesel exhausts were weighted to the C_9 to C_{14} range. This difference can be seen in the chromatograms (Fig. 19) obtained from samples collected under field conditions using the collection tubes. The numbered peaks in this chromatogram correspond to the numbered compounds listed in Table VII. The gasoline engine

Table VII. Organic components identified in diesel and gasoline exhaust.

Samples taken under field conditions	*Direct injection*
1. Isopentane	1. Methane
2. n-Pentane	2. Ethylene
3. Pentene	3. Ethane
4. 1, 3-Cyclopentadiene	4. Acetylene
5. 2-Methylpentane	5. Propane
6. Methylcyclopentane	6. Propene
7. n-Hexane	7. Propadiene
8. Benzene	8. C_4 Hydrocarbons
9. C_7 Hydrocarbons	9. C_5 Hydrocarbons
10. C_8 Hydrocarbons	10. C_6 Hydrocarbons
11. Toluene	11. Benzene
12. Xylenes	12. Toluene
13. C_3 Aromatic hydrocarbons	
14. C_4 Aromatic hydrocarbons	
15. C_5 Aromatic hydrocarbons	
16. Acetone	
17. Nitromethane	
18. Methacrolein	
19. Butyraldehyde	
20. Valeraldehyde	
21. C_9 Hydrocarbons	
22. C_{10} Hydrocarbons	
23. C_{11} Hydrocarbons	
24. C_{12} Hydrocarbons	
25. Naphthalene	
26. C_{13} Hydrocarbons	
27. Methylnaphthalene	
28. C_{14} Hydrocarbons	

exhaust is also characterized by large amounts of methane, ethylene, acetylene and C_3 to C_4 unsaturated hydrocarbons. The diesel engine, however, shows significantly smaller amounts of these exhaust chemicals, as shown in the chromatograms of exhaust samples (Fig. 20) taken at USA CRREL. In this case, the exhaust gases were analyzed by direct injection into the analytical equipment rather than by use of an adsorption tube. The numbered peaks in this chromatogram correspond to the numbered compounds listed in Table VII.

Aromatic hydrocarbons were found in substantial concentrations in all samples from both diesel and gasoline engines. No significant differences in these fractions could be attributed to engine class. Oxygenated compounds, primarily saturated and unsaturated aldehydes and ketones, were also present in both types of exhaust. Aliphatic nitro compounds, specifically nitromethane, were found in diesel exhaust and have been reported in gasoline exhaust as well. These types of components do not seem significant for classification. Sulfur-containing organics have also been observed at very low concentrations in diesel exhaust.[6] The levels at which these sulfur compounds are present, as well as the uncertainty of their presence in gasoline exhaust, make their use for vehicle classification unlikely.

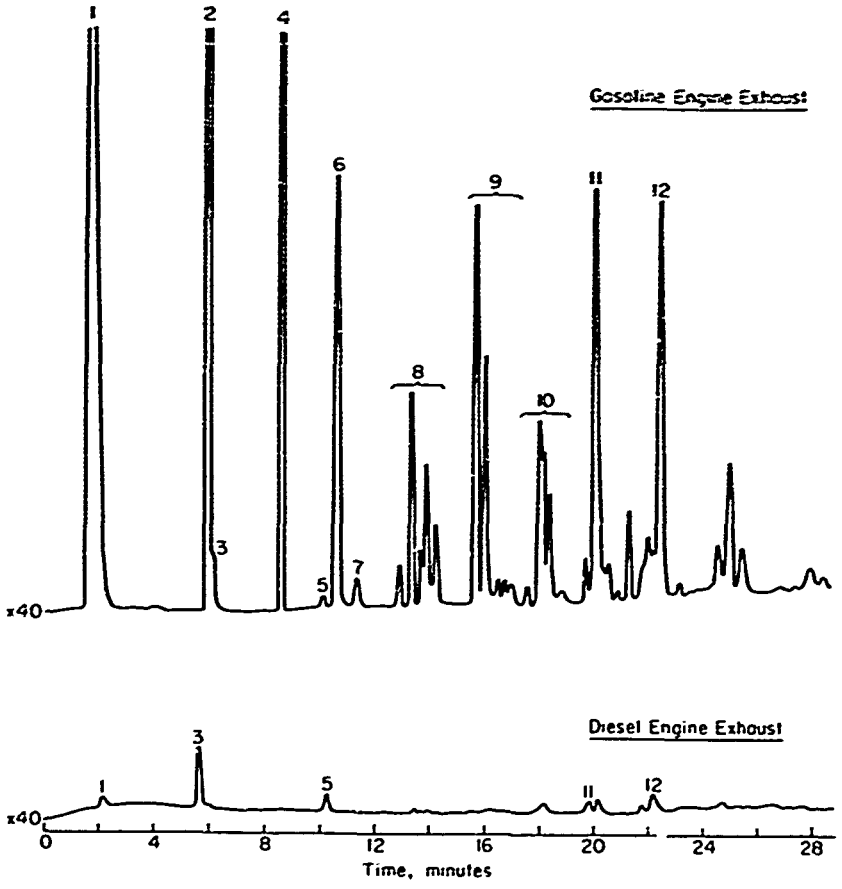

Figure 20. Typical chromatograms of organic fraction of vehicle exhaust obtained by direct injection.

[6] Dravnieks, A., A. O'Connell, R. Scholz and J.D. Stockham (1971) Gas chromatographic study of diesel exhaust using a two-column system, presented at ACS meeting of Division of Water, Air and Waste Chemistry, Los Angeles, 29 Mar.

Detection of Major Exhaust Components

The second approach to classification was directed toward establishing whether the simultaneous detection of several major exhaust constituents could be used to reliably classify diesel and gasoline vehicles. Although a specific experimental study was not conducted, it is possible to draw some conclusions using data obtained during field tests on detection conducted at Yuma, Arizona; Warren, Michigan; and Camp Grayling, Michigan. The parameters monitored during the field trials and the types of monitors used for detection included particulates (condensation nuclei), nitrogen oxides (chemiluminescence), total hydrocarbons (flame ionization), total sulfur (flame photometric) and carbon monoxide (infrared). The Honeywell ionization detector was also included although the constituents to which it responds are unknown. The pertinent data, which include those for all vehicle passes within 35 m at the three field trials, are summarized in Table VIII.

From this table it is apparent that the condensation nuclei detector is nonspecific and responds equally to diesel and gasoline powered vehicles. The same general characteristic can be noted for the chemiluminescence monitor. The flame photometric (sulfur) monitor, however, although its performance during field trials was inferior to that of either the condensation nuclei detector or the chemiluminescence monitor, showed high specificity to the diesel powered vehicles. This result agrees with the higher sulfur content of diesel fuel relative to gasoline. It is felt that the poor reponse characteristics of this type of monitor can be improved with experience in flame optimization. The flame ionization monitor (hydrocarbons) also showed poor response characteristics during field trials. It did, however, show specificity toward gasoline powered vehicles. This result agrees with our results in the molecular analysis experiment which showed significantly higher total organic output in the gasoline exhaust. The poor response characteristics for this type of monitor are also a function of flame optimization and can be improved. The carbon monoxide monitor was inoperable during the field trials and hence no data have been presented for it. It is felt that it would likely respond preferentially to gasoline exhaust, judging from the data shown in Table II.

Table VIII. Response of chemical sensors to diesel and gasoline military vehicles within a 35-m downwind range.

	*Vehicle type**			
	Diesel		*Gasoline*	
Sensor type	*Trials*	*Detections*	*Trials*	*Detections*
Condensation nuclei (Combustion particulates)	114	110	109	99
Chemiluminescence (Nitrogen oxides)	122	106	116	71
Honeywell ionization (Unknown)	82	57	77	39
Flame photometric (Sulfur)	114	67	111	2
Flame ionization (Hydrocarbons)	115	4	110	41

*Data obtained for the various models of gasoline and diesel vehicles tested are combined under each heading.

The configuration of the Honeywell ionization detector used in this study was that designed for chemical agent detection. Although the component to which it was responding is not known, its response generally corresponded to that of the chemiluminescence monitor. In the present configuration it tended to respond to both types of vehicles, with some small specificity toward diesel powered ones. It is felt that this type of detector can be configured to respond even more specifically toward the diesel engine exhaust by taking advantage of the significantly higher sulfur content of this exhaust.

Summary

Our results indicate that classification of diesel and gasoline vehicles can best be accomplished by a combination of two chemical sensors, at least one being sensitive to either total sulfur (diesel vehicles) or total hydrocarbons and/or carbon monoxide (gasoline vehicles). It could also be accomplished by monitoring the methane or C_2 to C_4 unsaturated hydrocarbons in conjunction with another sensor. This would require a higher level of detector sophistication, such as that of a field portable mass spectrometer and hence appears to be the least desirable of the two approaches. Higher order classification within engine type is uncertain but would certainly require a high level of detector sophistication such as a mass spectrometer. An extended exhaust signature program should be undertaken to further investigate this possibility.

CHEMICAL SENSOR CONCEPTS

Concurrently with field tests on the detectability of exhaust components for various military vehicles, a survey was made to identify types of chemical sensors which could potentially be developed to meet REMBASS requirements for vehicle surveillance. In conducting this evaluation, attention was first given to chemical sensors that had previously been evaluated for other military detection applications. Contact was then made with various commercial firms that produce chemical instrumentation and monitoring equipment which seemed to merit consideration. Since there has been virtually no work on development of chemical sensors for remote monitoring of vehicles, it has been necessary to project or estimate physical and performance characteristics that could be achieved after an appropriate development effort rather than to state current characteristics. Factors evaluated for a particular concept included selectivity for a given exhaust component, sensitivity or detection limits, response time after sample acquisition, weight, size and power requirements, and current state-of-the-art of development.

The chemical sensor concepts described in this section are limited to those which seemed to have reasonable merit, all factors considered. Although the survey was necessarily limited in scope because of the time frame of the study, it is felt that the most immediately promising concepts were identified. These concepts are shown in Table IX according to selectivity to various types of exhaust components. In certain cases, preferential response would require modification of the type of sensor currently available. Some of these sensors have undergone some development for military use, others are commercially available monitors or instruments, while some are available only as commercial prototypes. A number of the sensors in currently available configurations were utilized during field tests to establish the detectability of the various military vehicles.

The response of the various sensors to vehicles is shown in Table X. The type of response to all vehicles, or preferentially to gasoline or diesel vehicles, is based on experience in field tests in combination with knowledge of sensor characteristics in cases where no performance data are

Table IX. Response of chemical sensors to vehicle exhaust components.

			*Major exhaust constituent**						
Sensor concept	*Nearest example*	*Included in field tests*	*Combustion particulates*	*Nitrogen oxides*	*Carbon dioxide*	*Sulfur dioxide*	*Hydro-carbons*	*Carbon monoxide*	*Hydrogen*
Condensation nuclei	Army M3 Personnel Detector	Yes	X						
Honeywell ionization	Air Force Multiagent Detector	Yes		(X)		(X)	(X)		
Surface adsorption	Commercial monitor	Yes			(X)		X	X	
Chemiluminescence	Commercial monitor	Yes		X					
Flame ionization	Commercial monitor	Yes					X		
Flame photometric	Commercial monitor	Yes				X			
Infrared absorption	Commercial monitor	Yes			X		X	X	
Electron capture	Commercial monitor	No		X					
Thermal conductivity	Commercial monitor	No							X
Kryptonate	Commercial prototype	No		X			X	X	
UV-derivative	Commercial instrument	No		X		X			
UV correlation	Commercial instrument	No		X		X			
Mass spectrometer	Commercial prototype	No		X	X	X	X	X	X
Plasma chromatograph	Commercial instrument	No					X		

*Parentheses indicate that detector potentially could respond preferentially to constituent indicated.

Table X. Response of chemical sensors to diesel and gasoline vehicles.

	*Types of vehicles detectable**		
Sensor concept	*All vehicles*	*Gas preference*	*Diesel preference*
Condensation nuclei	X		
Honeywell ionization	(X)	(X)	(X)
Surface adsorption	(X)	X	
Chemiluminescence	X		
Flame ionization		X	
Flame photometric			X
Infrared absorption	X	X	
Electron capture	X		
Thermal conductivity		X	
Kryptonate	X	X	
UV-derivative	X		X
UV-correlation	X		X
Mass spectrometer	X	X	X
Plasma chromatograph		X	

*Although both diesel and gasoline exhaust contain all major constituents, the amount of a constituent varies depending on engine type so that a detector can be more sensitive to one type of vehicle. Parentheses indicate potential response after detector modification.

available. In practice, as shown in Table VIII, sensors that respond to combustion particulate matter and nitrogen oxides are general purpose detectors. Sensors that respond to sulfur preferentially detect diesel vehicles, while sensors that respond to hydrocarbons preferentially detect gasoline vehicles.

Although the detectability of vehicles is related to the concentration of the various exhaust components shown in Table II, sensor performance is difficult to estimate solely on the basis of exhaust concentration. Among the other factors that must be considered are detection limits of the required sensor as well as the normal concentration of a given component in the atmosphere. This is illustrated in Table XI, which was compiled in the process of attempting to explain some of the relative sensor responses observed during field tests. Sensor sensitivities given are believed to be practical under field conditions. The ambient concentrations are for remote or rural areas not directly influenced by local pollution sources. One of these two factors limits performance in that detection becomes more difficult as the exhaust becomes diluted to ambient levels, or the detection limit of the sensor is approached. Exhaust compositions shown were taken from Table II. The ratio of the exhaust concentration to the concentration of the detection sensitivity or ambient concentration, whichever is limiting, is termed the detection index (DI). This index, although extremely qualitative seems to correspond roughly to relative performance of the various sensors during field tests.

For example, by far the most superior performance was demonstrated by the condensation nuclei detector (DI = > 10^7) followed by the chemiluminescence detector (DI = 5×10^4). Moderate performance was shown by the flame photometric detector (DI = 10^4; diesel), followed by the flame ionization detector (DI = 5×10^3; gasoline). The response of the infrared absorption detector (DI = 400;

Table XI. Estimate of relative detectability of major exhaust components.

Factor	*Particulates by condensation nuclei*	*Nitrogen oxides by chemiluminescence*	*Carbon dioxide by IR*	*Carbon monoxide by IR*	*Hydrogen by thermal conductivity*	*Hydrogen by flame ionization*	*Sulfur by flame photometric*
Sensor sensitivity, ppm	100 N/cm³	0.01	10	100	10	0.1	0.01
Ambient atmosphere concentration, ppm	1000 N/cm³	<0.01	300	0.1	0.5	1	0.02
Limiting factor (Atm conc or sensitivity)	Atm	Sen	Sen	Sen	Sen	Atm	Atm
Concentration in exhaust, ppm Gasoline	$>10^{10}$	500	90,000	40,000	20,000	5,000	60
Concentration in exhaust, ppm Diesel				1,000	300	200	200
Detection index $= \frac{\text{(Exhaust conc)}}{\text{Limiting factor}}$ Gasoline	$>10^{7}$	50,000	9,000	400	2,000	5,000	3,000
Detection index $= \frac{\text{(Exhaust conc)}}{\text{Limiting factor}}$ Diesel				10	30	200	10,000
Classification Index $= \frac{\text{(Det index - gas)}}{\text{(Det index - diesel)}}$	1	1	1	40	67	25	0.33

gasoline) sensitive to carbon monoxide was very poor. However, much better performance should be expected from an infrared absorption detector sensitive to carbon dioxide (DI = 9×10^6). In comparison with other sensors, a thermal conductivity detector sensitive to hydrogen should respond with moderate performance to gasoline exhaust (DI = 2×10^5). Another factor termed the classification index (CI) was defined as the ratio of the detection indices for gasoline and diesel vehicles. For good classification performance, a sensor should have a high DI in combination with a high CI for gasoline vehicles or a low CI for diesel vehicles. Thus, for gasoline vehicles the flame ionization detector (DI = 5000, CI = 25) should be a better choice than the infrared absorption detector (DI = 400, CI = 40).

The various chemical sensor concepts are described below in terms of application to detection alone or to classification of gasoline and diesel powered vehicles. The first category includes only the simpler, lower-cost sensors even though some respond preferentially to gasoline or diesel vehicles. The classification sensors are either combinations of two detectors of which at least one responds preferentially to gasoline or diesel exhaust, or more complex detectors capable of simultaneously monitoring more than one exhaust component.

Performance characteristics in terms of detection range are estimated for 90% reliability of detection or classification as applicable. The ranges given are usually greater than would be indicated by review of field test data. However, actual downwind range should be better than shown by the data since changes in wind direction frequently occurred after a test was initiated. In some cases, difficulties with instrumentation are reflected in field test results. Allowance has also been made for increased performance that should result from experience with detector placement, and from sensor improvement in conjunction with a development effort. The ranges given for use of two sensors to avoid dependence on wind direction are judgment values based on limited field experience on detectors and detector placement. Physical characteristics of current sensors are also included in some cases with an estimate of the size, weight, and power requirements which can be anticipated based on experience in development of chemical alarm systems. Size and weight of power source are not included in these estimates.

The unit cost of a given sensor was estimated taking current costs and modification of current sensor design into account for production quantities of 1000 units. Development time through engineering development assumes an accelerated program. While some sensor concepts have undergone some advanced development, advanced development work is assumed in all cases. For some concepts, a limited amount of exploratory study is required concurrently with advanced development. Development costs were estimated in two ways. First, based upon guidance from USAMERDC,* costs were estimated to be 2000X unit cost for 1000 unit production. However, this cost estimate appeared to be too low in most cases considering that development costs should be based on all efforts required for completion of the engineering development program including all documentation, maintenance, training, and evaluation requirements for type classification standard A. These original figures were then adjusted to higher values when required to be consistent with costs previously encountered in development of chemical agent alarm systems. It is emphasized that development costs reported are rough estimates since time restraints did not permit a detailed cost analysis. The apparent higher cost for chemical sensors may well be due to the fact that most other types of sensors have already undergone a considerable amount of development for REMBASS-type applications. It is estimated that through 1971 more than 1.6 billion dollars have been expended on development of intrusion detection systems.[7] Another factor reflected in development and unit costs is that chemical sensors are generally more complex than other sensors.

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* USAMERDC has task responsibility for development of REMBASS sensors.

[7] Frost and Sullivan Co. (1971) Intrusion detection, weapons location, and sensor aided military markets. Camp Reports.

Chemical Sensors for Vehicle Detection

Condensation nuclei detector

Vehicle exhaust contains large numbers of combustion product particles in the size range of 0.001 to 0.1 μ in diameter. When present under certain conditions in air supersaturated with water vapor, these particles act as nuclei for condensation of the vapor to form water droplets. Such particles are termed condensation nuclei (CN). The occurrence of the water droplets, which are easily measured by light attenuation using a photoelectric cell, provides the basis for this extremely sensitive vehicle detection technique. Even a small utility engine produces more than 10^{15} particles/sec in its exhaust. A CN detector (CND) easily responds to as little as 10^{3} particles/cm^{3}, which is about the normal concentration of CN in rural atmospheric air. Detector response time is less than 2 sec.

The CND (Fig. 21) has undergone some development for application to personnel detection. Although the CND is not sensitive to personnel directly, it does detect particulate matter generated in conjunction with personnel activities. The current version is the M3 Personnel Detector. This detector operates on an adiabatic expansion principle which requires strong suction and mechanical valving. Another type of CN detector is now being developed based on a continuous-flow configuration which is simpler, more reliable, less expensive, and requires less power. In this case, sample air is pumped over an electrically heated wick to introduce hot water vapor. Supersaturation of the air with water is maintained as the sample moves continuously through the system.

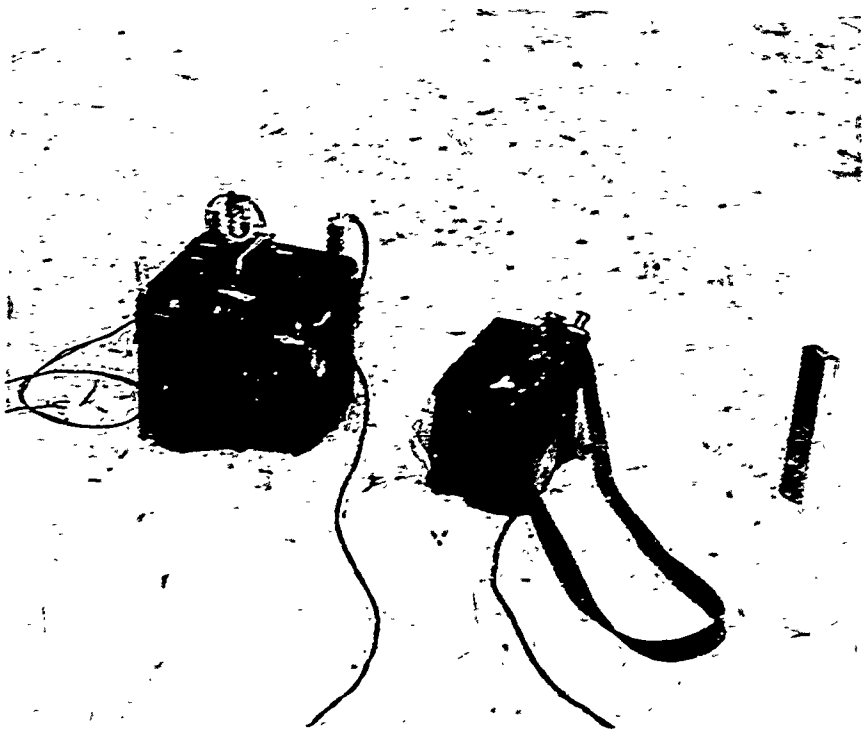

Figure 21. Condensation nuclei detector.

The CND showed excellent performance during field tests (Table VI). Reliable detection can be obtained at downwind ranges of more than 400 and 100 m in open and wooded terrain, respectively. By using 2 or more detectors, a detection range of 100 m independent of wind direction should be possible. Longer ranges can be attained with a reduction in detection probability. The CND, like other chemical sensors, responds to local combustion sources such as fires. However, during field tests in rural areas no signals were observed that could not be attributed to vehicles.

One limitation of the detector is that ambient temperatures must be above freezing since water is required. Consideration should be given to substituting another liquid with a lower freezing point. The CND is not influenced by other environmental conditions such as precipitation or pressure. Although it would normally be hand emplaced, the CND could be designed for air deployment.

Current prototype versions of the continuous-flow CND weigh less than 5 lb and have a 3-w power requirement. Projected physical properties are: size 75 in.^{3}, weight 2.5 lb, and power requirement 2-w. Unit costs should be about $300 for 1000-unit production. Development costs are estimated at $3M over a 3-yr period.

Honeywell ionization detector

The Honeywell ionization detector (HID) is currently being developed as a portable, automatic, all-electronic device for continuous use in chemical agent detection. The current design provides simultaneous detection of two types of agents at extremely low concentrations. Thus, potential for high specificity and sensitivity has been demonstrated. The basic concept of detection is the formation and collection of molecular ions contained in a stream of sample air to generate an electrical signal. The incoming air stream passes through three ionization cells connected in series. Each cell contains a small radioactive tritium source which emits low energy electrons. The interaction of the electrons with sample molecules results in molecular ions which are collected with various efficiencies downstream, depending on internal flow geometry of the cells, electrode arrangement, and electrical field strength. These parameters can each be varied to adjust sensitivity and selectivity for a given type of chemical. Response time of the detector is less than 2 sec.

The HID was tested for vehicle detection during field studies. In order to obtain response to vehicle exhausts it was necessary to modify the configuration of the cell normally sensitive to chemical agents. No extensive evaluation of the proper configuration could be made within the scope of the study, so it was necessary to establish detector parameters which appeared promising based on results of earlier screening tests for chemical agents. Nevertheless, results during field tests were encouraging. The detector responded well to both diesel and gasoline vehicles at ranges up to 35 m (Table VI). The exhaust components to which the detector responded are unknown but should be determined. It is projected that the HID should show good performance at downwind ranges of 150 m in open terrain and 50 m in wooded terrain. Using two detectors, a range of 50 m should be obtained independent of wind direction. No signals that were not due to vehicles were observed during field tests in rural areas. The detector could be operated at subfreezing temperatures. The detector would normally be hand emplaced but could be designed for air deployment.

The HID in its present configuration (Fig. 22) with attached 115-VAC power supply weighs about 15 lb and has a volume of 0.3 ft^3. The unit is operable with batteries having a 10-w power consumption at 70°F. The portable detector could be engineered to a 200-in.^{3} size, 2.5 lb weight, and a 4-watt power requirement. Unit costs in production of 1000-unit quantities are estimated at $600. Development costs are estimated at $3.5M over a 3-yr period.

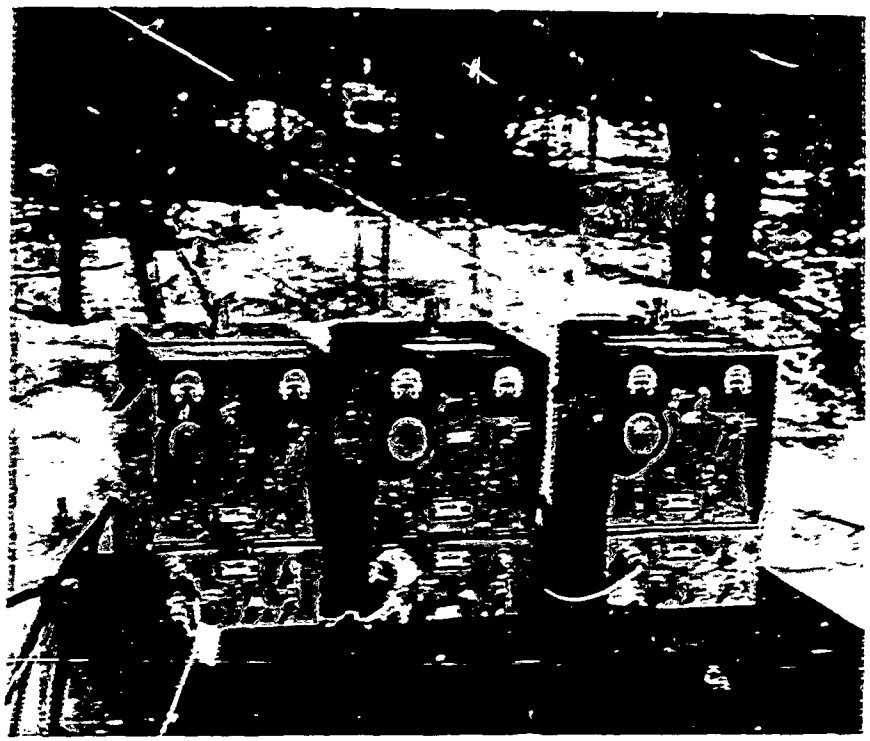

Figure 22. Honeywell ionization detectors.

Surface adsorption detector

The surface adsorption detector (SAD) concept covers several types of sensor devices. In each case, a response is due to interaction of exhaust chemicals with surface components of a simple sensing element. For example, in the case of a piezoelectric crystal, adsorption of gases alters the crystal mass which is reflected in terms of a detectable change in resonance frequency. Other sensor elements consist of solid electrolyte substrates coated with thin metallic films, although other film material could be utilized in some cases to vary specificity. As adsorbed gases diffuse through the film coating, the ionic conductivity of the electrolyte is altered, the volume of the electrolyte can change, or oxidation/reduction reactions involving the solid electrolyte, and/or the metal film interface can occur depending on the particular type of sensing element.

Specificity and sensitivity can be varied to some degree by variation in the magnitude of applied biases and choice of sensor materials. The projected sensitivity of these devices is on the order of 10 ppm. Use is limited to detection of carbon dioxide from both diesel and gasoline vehicles, and carbon monoxide or possibly hydrocarbons from gasoline vehicles.

Most of the various types of SAD sensors are still in the research stages. However, a small solid state sensor for monitoring reducible gases including carbon dioxide has been reported. Another type of adsorption sensor capable of monitoring carbon monoxide and hydrocarbons that are oxidizable gases is commercially available. A prototype of this type of sensor, shown in Figure 23, was constructed by USA CRREL for use in vehicle detection studies. Operational difficulties prevented collection of sufficient data to permit analysis of detection capability.

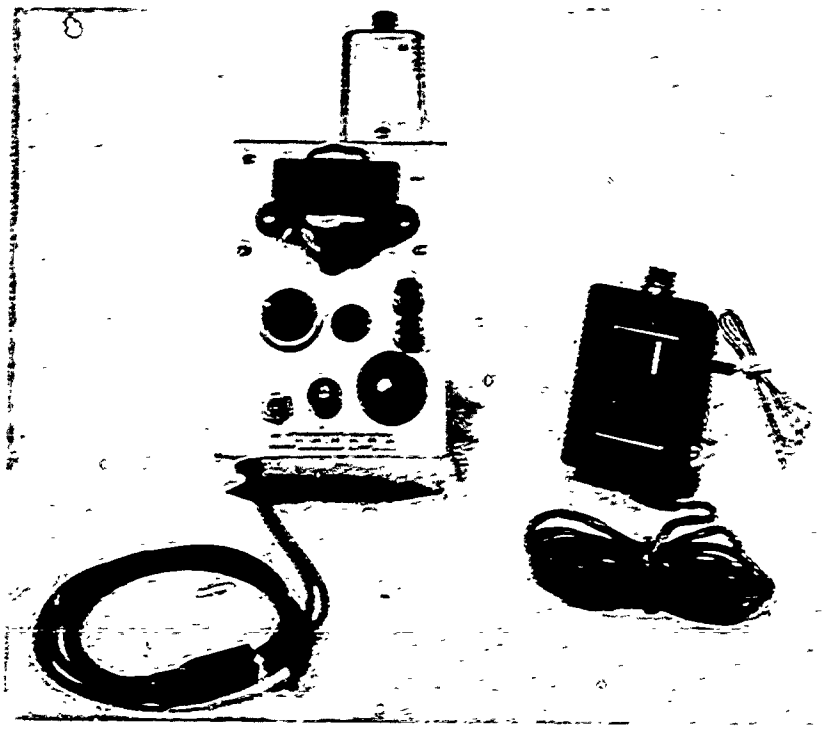

Figure 23. Surface adsorption detectors.

At short ranges of several meters it was possible to consistently detect gasoline engines presumably in response to carbon monoxide and hydrocarbons. The reason for the poor performance in terms of detection range is that the sensor was configured for use at normal room temperature in the laboratory. The tests conducted in the field at Camp Grayling, Michigan, were conducted when the ambient temperature was 40-50°F or less. Consequently, the sensor element temperature was too low for optimum response. This problem can be corrected by providing a compensating mechanism to maintain sensor temperature at a preset value. It should then be possible to detect gasoline vehicles at ranges up to 30 m. Development of the carbon dioxide sensor would permit detection of both diesel and gasoline powered vehicles. These sensors could be used at subfreezing temperatures provided that the sensor element temperature is maintained at the appropriate level. Response time was observed to be immediate during field tests.

Although there is a relatively high risk in development of this type of sensor due to the state of the art and low demonstrated performance, the physical and cost characteristics are highly favorable. Detectors of this type currently are about 5 in.^{3} in size and 0.2 lb in weight with a power requirement of about 2 w. It should be possible to reduce power requirements. However, additional feasibility work must be conducted before final performance and physical characteristics can be stated. It should be possible to use all modes of detector emplacement if detectors are designed to withstand shock. Current detector costs are about $50/unit. Costs for a vehicle detection version should not exceed $100/unit on a 1000-unit production basis. Development costs are estimated at $3M over a 3-yr period.

Chemiluminescence detector

The chemiluminescence (CD) concept has recently been applied to development of equipment for monitoring nitrogen oxides. Since nitric oxide (NO) is the most abundant nitrogen oxide in exhausts, sensing of this component should provide a means of vehicle detection. The sample gas containing NO is drawn through a chamber and reacted with ozone (O_3) produced by a small O_3 generator. The reaction of O_3 with NO produces nitrogen dioxide (NO_2) with the emission of light. The light emitted is passed through an optical filter to a photomultiplier tube. The signal generated is proportional to the specific amount of NO present in the original air. Detection sensitivity is about 0.01 ppm which approaches the NO concentration in rural atmospheres. This type of device is capable of real-time monitoring with a response time of less than 10 sec.

A commercial monitor capable of detecting NO, NO_2, or NO + NO_2 was utilized during field tests. The performance of this instrument was good with best response in the NO or NO + NO_2 operating mode. Good performance, considering the state of the art, was obtained at downwind ranges up to 150 m in open terrain and up to 30 m in wooded terrain (Table V). High performance with sensor improvement should be possible up to 150 m and 50 m in open and wooded terrain, respectively. A range of 50 m independent of wind direction should be obtained using 2 detectors.

The currently available chemiluminescence monitors operate on line power, weight about 40 lb and are about 2 ft^3 in volume. Thermoelectric elements are used to cool the photomultiplier tube and oxygen is required for the ozone generator. However, much could be done to simplify and reconfigure this device for vehicle detection. Estimates of attainable physical characteristics are 200 $in.^3$ in size and 2.5 lb in weight with a 4-w power requirement. Unit costs based on production of 1000 units are estimated at $2000. Development costs are estimated to be $5M over a 4-yr period.

Infrared absorption detector

Molecules absorb energy in the infrared region of the electromagnetic spectrum due to interval vibration of component atoms. The wavelengths or frequencies at which absorption occurs depend on the types of atoms involved as well as overall molecular structure. Intensity of absorption is related to molecular characteristics and the concentration of a chemical. Consequently, the infrared absorption spectrum, a presentation of absorption intensity versus wavelength, is characteristic for a given type of molecule. Monitoring of selected infrared absorption bands would serve as the basis for detection of several types of exhaust chemicals. Absorption of infrared energy by carbon dioxide could provide detection of both gasoline and diesel powered vehicles. Absorption bands indicative of hydrocarbons or carbon monoxide would be more useful for detection of gasoline exhausts.

Several concepts for infrared absorption devices are currently under consideration for chemical agent monitoring. One approach, the LOPAIR (Long Path Infrared) is an active system under development which consists of a tripod-mounted transmitter-receiver and a reflector separated by a distance of about 400 m. The system monitors three infrared wavelengths where absorption occurs due to the presence in the optical path of trace quantities of selected chemical agents. A passive version of LOPAIR under investigation operates without an active infrared source. In this configuration, the natural background acts as the source of infrared energy, the atmospheric path contains the sample, and the LOPAIR device is the detector. The goal is to monitor paths of several miles for chemical agents. Neither the active or passive LOPAIR systems have been evaluated for sensitivity to vehicle exhaust components so performance characteristics for vehicle detection are not known. Although this concept is not considered further at this time for vehicle detection, future studies should take this type of equipment into account as the state of the art of LOPAIR systems advances.

Another type of commercially available infrared monitor assembled to be specific for carbon monoxide was included in field studies. This type of instrument is also commonly available for monitoring carbon dioxide and hydrocarbons. The atmospheric sample is continuously drawn through a sample cell through which an infrared beam is passed to a sensor. Absorption of infrared radiation at a given wavelength is proportional to sample concentration. Performance during field tests was so poor that results are not given. However, this is thought to be due in part to the configuration of the particular instrument used. Also, for carbon dioxide, this type of monitor should be at least ten times more sensitive than for carbon monoxide at a given concentration. Laboratory work sponsored by Edgewood Arsenal using a short path infrared system with exhaust vapors from gasoline indicated strong absorption bands apparently due to ethylene. A portable infrared monitor with tuneable wavelength and a variable path-length cell is available commercially. Based on monitoring of carbon dioxide, it is projected that vehicle detection should be possible at downwind ranges up to 75 m and 30 m in open and wooded terrain, respectively. Using an array of 2 detectors, ranges of 30 m should be attainable regardless of wind direction.

Projected physical properties for infrared absorption detectors (IAD) are 200-in.^{3} size, 2.5-lb weight, and 4-w power consumption. Unit costs should be about $1500 for 1000-unit production. Development costs are estimated at $5M for a 4-yr period.

Electron capture detector

Many chemical compounds have a strong affinity for electrons. The electron capture detector (ECD) based upon exposing volatile chemicals with this property to low energy electrons has been developed for use in analytical chemistry applications. Usually, radioactive tritium contained in foil is used as the low energy electron source. The radioactive source is arranged near electrodes which measure electron current. As a sample passes through the detector cell, electrons are removed in formation of negative ions which causes a measurable decrease in electron current. This type of detector is extremely sensitive to electron capturing compounds yet highly insensitive to other noncapturing chemicals.

For vehicle detection, it should be possible to develop a ECD sensitive to nitrogen dioxide (NO_2) produced by conversion of nitrous oxide (NO) predominately present in vehicle exhaust. This concept has not been evaluated since a commercial source of an ECD with this configuration could not be located. However, this approach seems within the state of the art since a portable ECD monitor is available for detecting leaks of refrigerants and other types of electron capturing compounds. For leak-test applications, the sample gas is allowed to diffuse across a membrane into a stream of carrier gas which flows through a detector cell. Apparently, the membrane serves to reduce influx of atmospheric oxygen which is electron capturing as well as to contain the particular carrier gas which is required to maintain high sensitivity.

The ECD would probably show satisfactory results at downwind ranges up to 75 m in open terrain. In wooded terrain or using 2 detectors to reduce dependence on wind direction, a range of 30 m seems practical. Physical properties should approach a size of 200 in.^{3} a weight of 2.5 lb, with a power requirement of 3 w. Unit costs should not exceed $600 on 1000-unit production basis. Development costs are estimated at $4M over a 4-yr period.

Kryptonate detector

Kryptonates are solids into which the radioisotope Krypton-85 has been incorporated. Radioactive krypton released upon disturbance of the surface layer forms the basis for methods of trace gas analysis. Specificity for a given type of gas is obtained by careful selection of the substrate solid.

This concept is currently being explored for application to analysis of exhaust pollutants. Prototype systems have been developed for nitrogen oxides, carbon monoxide, and hydrocarbons. Consequently, there is potential for using the technique for general-purpose vehicle detection, and for gasoline vehicle detection. Detection limits are claimed to be 2 ppm for nitrogen oxides, 125 ppm for carbon monoxide, and 15 ppm for hydrocarbons. Although these sensitivities are marginal for use in vehicle detection, there is room for improvement through appropriate development efforts. In using the krypton detector (KD) sample air is drawn through a cell containing the krypton material. The radioactive krypton released by chemical reaction enters the gas stream which then passes through a counting chamber containing a radiation sensor. The output of this sensor is proportional to the concentration of a target component in the sample air.

The KD with improved sensitivity could show good performance at ranges of 75 m in open terrain and 30 m in wooded terrain. Use of 2 detectors should permit detection at 30 m independent of wind direction. It is projected that this type of detector would be about 200 in.^{3} in size, weigh 2.5 lb and require 4 w in power. Unit costs should not exceed $1600 on a 1000-unit basis. Development costs would probably be $5M over a 4-yr period.

Thermal conductivity detector

Another concept which may be suitable for detection of gasoline powered vehicles is the thermal conductivity detector (TCD). Such devices are in common use in gas chromatograph analytical instruments. In normal operation, a carrier gas, usually helium or hydrogen, passes over reference and detector sensor elements which may be either paired hot filaments or thermistors arranged in a bridge circuit. The temperature of the sensor elements is determined by the rate of heat loss by conduction through the carrier gas. The presence of a sample component changes the thermal conductivity of the gas passing through the detector side of the cell. This is reflected in a change of sensor element temperature causing an electrical output from the bridge circuit.

For detection of gasoline exhausts, atmospheric air would be pumped through a thermistor-type TCD cell. The presence of hydrogen gas in the atmosphere from gasoline vehicles should be detectable at levels of 10 ppm. This approach has been used in simple devices commercially available for detection of helium leaks. For exhausts, detection ranges up to 30 m in all types of terrain independent of wind direction should be possible. Physical characteristics and unit-cost considerations would generally be quite favorable in comparison with other types of chemical sensors. Size is estimated at 100 in.^{3}, weight 0.5 lb, with a power requirement of 2 w. Unit costs based on 1000-unit production are estimated at $250 with development costs at $3M over a 3-yr period.

Flame ionization detector

One of the most sensitive methods for detection of organic compounds is the flame ionization detector (FID). This device is commonly used in gas chromatographic instruments and in hydrocarbon monitors for pollution measurements. The detector consists of a small hydrogen flame burning in an excess of air. Sample air is mixed with the hydrogen fuel gas prior to entering the burner housing. Hydrocarbons in the sample air are oxidized to carbon dioxide but charged fragments are formed as intermediate reaction products. These ionic fragments are collected on suitably arranged electrodes which produce a current proportional to the amount of hydrocarbons entering the flame per unit time.

A hydrocarbon analyzer was used during field tests. This instrument responded preferentially to exhaust from gasoline vehicles. Although performance was generally poor, this is thought to have been due to malfunction problems of the particular detector. It should be possible to obtain good detector performance for gasoline vehicles at ranges up to 100 m in open terrain and 30 m in

wooded terrain. Use of 2 detectors should permit detection up to 30 m independent of wind direction. A FID should be about 200 in.^{3} in size, 3 lb in weight, and have a power requirement of about 3 w. Estimated costs per unit are $1000 on a 1000-unit production basis. Development costs are estimated at $5M over a 4-yr period.

Flame photometric detector

The design of a flame photometric detector (FPD) is similar in many respects to that of a flame ionization detector. However, in this case, fuel air and the sample flow through a burner jet into a hydrogen-rich atmosphere which produces a reducing flame. Compounds containing sulfur undergo electronic transformations which result in the emission of light at wavelengths specific for the presence of sulfur. This emission is then detected using a photomultiplier tube, the electrical output of which is related to the amount of sulfur present in the sample air. These detectors are commonly used in both gas chromatographic instrumentation and sulfur monitors available for pollution studies.

A sulfur monitor was used during field tests. Diesel vehicles were preferentially detected with detection range limited to about 35 m. By improvements in detector design and operational characteristics, it might be possible to detect diesel vehicles up to 100 m in open terrain and 30 m in wooded terrain. Detection at 30 m should be obtainable independent of wind direction using 2 detectors. Size is estimated at 200 in.^{3}, weight at 3 lb and power requirement at 3 w. Unit costs are estimated at $1500 for 1000-unit production. Development costs are estimated at $5M over a 4-yr period.

Chemical Sensors for Vehicle Classification

Consideration of available information indicates a reasonable potential for employing chemical sensors to classify diesel and gasoline powered vehicles. Although additional study is required on the feasibility of classification even at this level, a goal of 90% detection and 90% correct classification seems attainable. This could be accomplished by use of a chemical classifier system consisting of either two simple sensors, each sensitive to a different exhaust component, or a more complex chemical instrument capable of simultaneously monitoring more than one type of exhaust chemical.

Following the approach based on use of two simple sensors, many combinations of detectors previously described are possible (Table XII). In certain cases, one sensor would detect either particulate matter, nitrogen oxides, or carbon dioxide in response to all types of vehicles [indicated by (V)]. The other sensor could respond to sulfur to indicate that the vehicle detected was diesel [indicated by (V/D)], or to carbon monoxide, hydrocarbons, or hydrogen to indicate that the vehicle was gasoline powered [indicated by (V/G)]. In other combinations, one sensor would respond preferentially to diesel exhaust while the other would indicate gasoline vehicles [indicated by (D/G)]. In order to decide which combination of chemical sensors showed the most immediate promise, a preliminary trade-off determination was made with the result that combinations which included sensors with characteristics most suitable for use as vehicle detectors should also be given first priority at this time for consideration in development of a vehicle classifier. These selected sensor combinations as well as other types of chemical concepts applicable to vehicle classification are described below.

Table XII. Combinations of chemical detectors for classification of diesel and gasoline powered vehicles.

CND (P)	HID (NO_x)	HID (S)	HID (HC)	SAD (CO_2)	SAD (CO/HC)	CID (NO_x)	FID (HC)	IRD (CO_2)	IRD (CO/HC)	ECD (NO_x)	TCD (H_2)	KD (NO_x)	KD (CO/HC)	FPD (S)
CND(P)		V/D	V/G		V/G		V/G		V/G		V/G		V/G	V/D
HID(NO_x)		V/D	V/G		V/G		V/G		V/G		V/G		V/G	V/D
HID(S)			D/G	V/D	D/G	V/D	D/G	V/D	D/G	V/D	D/G	V/D	D/G	
HID(HC)				V/G		V/G		V/G		V/G		V/G		D/G
SAD(CO_2)					V/G		V/G		V/G		V/G		V/G	V/D
SAD(CO/HC)						V/G		V/G		V/G		V/G		D/G
CID(NO_x)							V/G		V/G		V/G		V/G	V/D
FID(HC)								V/G		V/G		V/G		D/G
IRD(CO_2)									V/G		V/G		V/G	V/D
IRD(CO/HC)										V/G		V/G		D/G
ECD(NO_x)											V/G		V/G	V/D
TCD(H_2)												V/G		D/G
KD(NO_x)													V/G	V/D
KD(CO/HC)														D/G
FPD(S)														

Detector

CND = Condensation nuclei
HID = Honeywell ionization
SAD = Surface adsorption
CID = Chemiluminescence
FID = Flame ionization
IRD = Infrared
ECD = Electron capture
TCD = Thermal conductivity
KD = Kryptonate
FPD = Flame photometric

Exhaust component

P = Particulates
NO_x = Nitrogen oxides
S = Sulfur
HC = Hydrocarbons
CO_2 = Carbon dioxide
CO = Carbon monoxide
H_2 = Hydrogen

Vehicle

V = all vehicles
D = Diesel
G = Gasoline

Dual Honeywell ionization classifier

The Honeywell ionization detector (HID) currently used is selectively responsive to two types of chemical agents with a demonstrated high sensitivity. The characteristics of the HID in relation to vehicle detection were described previously. There is potential for configuring this sensor to be specific for either nitrogen oxides, sulfur, or organic hydrocarbon exhaust components. Thus, the instrument could potentially be used to be responsive to all vehicles and diesel (V/D), or gasoline vehicles (V/G), or to respond either to gasoline or diesel vehicles (D/G). Feasibility studies must be conducted to determine which approach would show the best performance. Although there is a risk involved that selectivity for one or more of the various exhaust components could not be developed, the availability of several options in configuration increases the probability of success.

The HID used as a classifier should show the same performance characteristics as when used as a detector. Projected ranges for downwind detection are 150 m and 50 m in open and wooded terrain, respectively. By using 2 classifiers, a 50-m range should be possible independent of wind direction. Projected physical characteristics are 300 in.^{3} in size, 3 lb in weight, and a power requirement of 5 w. Unit costs should not exceed $750 for 1000-unit production. The development cost is estimated at $4.5M over a 4-yr period.

Condensation nuclei/Honeywell ionization classifier

Both of the sensors in this combination have been described for use as detectors. The CND shows no selectivity to gasoline or diesel powered vehicles. The HID shows potential for modification for selectivity to sulfur indicative of diesel vehicles and for organic hydrocarbons indicative of gasoline vehicles. Thus, potential exists for using a combined CN/HI classifier to determine whether a vehicle detected is gasoline (V/G) or diesel (V/D) powered. Further study is required to evaluate the merit of this approach but the availability of two options for configuring the HID increases the probability of success.

The HID would limit the range of this type of classifier. Projected downwind detection ranges are 150 m and 50 m in open and wooded terrain, respectively, with a 50-m range independent of wind direction when using 2 sensor systems. The classifier would be about 275 in.^{3} in volume, require 4 w power, and weigh about 5 lb. Unit costs are estimated at $1000 for 1000-unit production. Development costs are estimated at $6M over a 4-yr period.

Honeywell ionization/surface adsorption classifier

Both the Honeywell ionization (HID) and the surface adsorption detectors (SAD) have been described for application to vehicle detection. The HID has also been described for use as a classifier alone or in combination with the condensation nuclei detector.

In conjunction with the SAD, the HID could be used in a configuration with sensitivity to nitrogen oxides indicated for all vehicles, sulfur compounds selective for diesel vehicles, or organic hydrocarbons for preference to gasoline powered vehicles.

There are a number of ways in which these two sensors could be combined as a classifier. The HID sensitive to nitrogen oxides in combination with a SAD which responds to carbon monoxide plus hydrocarbons would indicate whether a detected vehicle was gasoline powered (V/G). The same distinction, V/G, could be made using a SAD responsive to carbon dioxide and a HID selective for organic hydrocarbons. Use of a SAD sensitive to carbon dioxide and a HID selective for sulfur would permit evaluation if a detected vehicle were diesel powered (V/D). Combination of a sulfur sensitive HID and a carbon monoxide plus hydrocarbon sensitive SAD would allow direct response to both diesel and gasoline vehicles (D/G). The proper configuration to use depends on results of studies required to evaluate response characteristics of both the HID and SAD to diesel and gasoline exhaust emissions. As in the case of other detectors, the availability of several options for configuration reduces the risk in development of a classifier of this type.

The range of a HID/SAD classifier would likely be limited by the SAD component. Projected range both downwind and independent of wind direction using 2 classifier systems would be about 30 m. The HID/SAD classifier should be about 200 in.^{3} in volume, 2.5 lb in weight and have a power requirement of 5 w. Unit costs are estimated at $700 for 1000-unit production. Development costs over a 4-yr period are estimated at $5.5M.

Condensation nuclei/surface adsorption classifier

The condensation nuclei detector (CND) responds to particulate matter present in the exhaust of both gasoline and diesel vehicles. Combination of the CND with a surface adsorption detector (SAD) responsive to carbon monoxide plus hydrocarbons would allow determination that a detected vehicle was gasoline powered (V/G). The range of this classifier would be limited by the SAD. However, reliability of detection at short range would be high. The range of the CND/SAD combination would probably not exceed 30 m, regardless of terrain characteristics. With 2 systems, classification range would probably be up to 30 m independent of wind direction. The combined CND/SAD classifier would have a volume of 75 in.^{3}, weigh 2.5 lb, and have a power requirement of 4 w. Unit costs should not exceed $500. Estimated development costs are $5M over a 3.5-yr period.

Dual surface adsorption classifier

The operation of a surface adsorption sensor was described in the section on chemical detectors. Use of the SAD where oxidation/reduction reactions occur seems to be the most promising approach for vehicle detection. Combining one sensor of this type that is responsive to all vehicles due to reduction of carbon dioxide from exhausts with another sensor that oxidizes carbon monoxide and hydrocarbons emitted by gasoline powered vehicles, would result in a classifier that would determine if a vehicle detected is gasoline powered (V/G).

This approach involves a considerable risk, because in field tests the carbon monoxide/hydrocarbon SAD showed poor performance, and because a carbon dioxide sensitive device is not currently commercially available. Also, detection range would likely be limited to 30 m whether downwind or independent of wind direction using 2 such classifiers. However, this type of classifier seems worth considering since it would have the most desirable physical characteristics and a cost advantage over other chemical classifiers. In terms of size, it would occupy a volume less than 10 in.^{3}, weigh about 0.2 lb, and have a power requirement of 3 w. Unit costs are estimated at $150 for 1000-unit production. Development costs are estimated at $4M over a 3-yr period.

Flame ionization/flame photometric classifier

Flame ionization detectors (FID) and flame photometric detectors (FPD) were discussed previously for application to detection of hydrocarbon and sulfur emissions from gasoline and diesel powered vehicles, respectively. Both techniques require combustion of the characteristic exhaust component in a flame. Although a different detector configuration is required for performance optimization, the possibility exists that sufficient sensitivity could be obtained utilizing a common burner. Using this system, response of the FID would be preferential for gasoline vehicles while FPD response would indicate detection of a diesel vehicle (D/G). Correct classification probability could possibly be increased by use of relative response of both detectors to a given vehicle. The sensitivity of the FID could be increased to gasoline vehicle by catalytic conversion of carbon monoxide predominately present in gasoline exhaust to methane.

Range of the FID/FPD classifier would likely be limited by the FID. Although the particular hydrocarbon analyzer containing a FID used during field tests performed poorly due to malfunction problems, it is projected that a FID/FPD classifier could have a useful range of 100 m in open

terrain and 30 m in wooded terrain. Range independent of wind direction using two classifiers would probably be limited to 30 m. The size of the FID/FPD classifier could be reduced to 200 in.^{3} with a power requirement of 3 w and a weight of 5 lb. Unit cost for production of 1000-units is estimated at $2000. Development costs over a 4-yr period would likely approach $7M.

UV-correlation classifier

The correlation spectrometer (CS) has been tested as a remote sensor for use in vehicle detection in a passive mode which is independent of wind direction and does not require pumping of sample air through the system. The principle of detection is based upon the absorption of ultraviolet radiation by exhaust components. For vehicle classification, both nitrogen dioxide and sulfur dioxide can be monitored simultaneously on a continuous basis. A separate photomultiplier tube is used for each gas with signals independently processed. At night an artificial light source must be provided. However, during the day only natural illumination is required. In the absence of a vehicle emissions, the background signals depend on the nature of the light source as well as environmental factors which alter spectral characteristics. The absorption of energy by vehicle emission components causes an abnormal response which for nitrogen dioxide can be interpreted as a detection. The presence of sulfur dioxide should indicate whether the vehicle is diesel powered (V/D).

Performance of the model tested was very marginal for vehicle detection although the feasibility of this concept was demonstrated. An increase in sensitivity of at least a factor of 10 seemed required for practical application. This increase in performance is claimed to be technically feasible. Detection ranges probably up to 150 m would be possible in open terrain after a suitable development effort. Range in wooded terrain would be limited by vegetation density.

The prototype unit tested for daytime use occupied a volume of 2160 in.^{3}, weighed 38 lb and had a power requirement of 10-18 w. A substantial improvement in physical characteristics should be possible with estimated reduction in size to 400 in.^{3}, weight to 5 lb, and power requirements to 5 w. Current models cost $10,000 to $12,000 depending on the number of gases to be monitored. For production quantities, unit costs of $3000 seem reasonable. Development costs of $8M over a period of 6 years would be required considering the state of the art.

UV-derivative classifier

This sensor concept is based on the absorption of ultraviolet radiation by nitrogen oxide and sulfur dioxide components of exhausts. This type of classifier would indicate that a detected vehicle is diesel powered (V/D). The UV-derivative spectrometer (DS) measures the curvature of absorption peaks specific for these compounds as sample air is drawn through the instrument. The DS is highly specific and sensitive, with detection limits in the 5-10 ppb range which should make a classifier useful at downwind ranges up to 100 m in open terrain and 30 m in wooded terrain. By use of 2 classifier systems, ranges up to 50 m independent of wind direction should be possible. Size is estimated at 400 in.^{3} with a weight of 5 lb, and a 10 w power requirement. Current models cost $5000 to $12,000 depending on configuration. On a production basis, costs for a classifier could be reduced as low as $3000. Development costs are estimated at $6M over a period of 5 years.

Mass spectrometer classifier

The mass spectrometer (MS) is a complex instrument originally developed for study of fundamental physical chemical processes which has in recent years been extensively utilized in the analytical chemistry field. Emphasis is now being placed on development of miniaturized versions

[8] U.S. Army Land Warfare Laboratory (1971) Spectrometer sensors investigation. Technical Report No. LWL-CR-05670.

of the MS for NASA applications and for use in pollutant monitoring problems. Application of the MS to trace gas detection for military purposes is under investigation. Major state-of-the-art advances are required before this type of sensor could be used in a portable, remote mode but the MS is the type of equipment required before detailed classification of vehicles could be possible by trace gas analysis.

There are a number of types of MS, but the general operational characteristics are similar for those potentially useful for trace gas detection. The sample is introduced using one of several techniques into a system that is maintained under high vacuum. Use of semipermeable membranes through which components of interest can selectively diffuse is gaining in popularity as an approach for continuous sampling of air. The sample molecules then pass through a region where fragmentation is induced, commonly by electron bombardment. The charged ionic fragments, each with a specific mass, are next directed through an electric field and/or a magnetic sector to a detector where a response is recorded. By controlled variation of the magnetic field strength, the ionic fragments sequentially reach the detector in order of mass to charge ratio (m/e). The resulting mass spectrum or time output in terms of signal intensity versus m/e is characteristic for each individual compound. For a complex mixture of volatile compounds, such as represented by vehicle exhaust, the mass spectrum is difficult to interpret in terms of individual components. However, this degree of complexity is what could make the MS useful for classification of vehicles which operate on the same type of fuel since gross composition of exhaust does not appear to vary in a manner which would allow classification at this level using simple detectors. The application of this concept remains to be evaluated for vehicle classification. The approach to take seems to be pattern analysis of a sufficiently large number of signature mass spectra to be of statistical significance. Equipment is currently available which is suitable for this type of feasibility study.

At this stage it seems premature to speculate on performance characteristics of a MS classifier. However, sensitivity is quite good, so downwind detection ranges in open terrain of 100 m and 30 m in wooded terrain seem reasonable. Using 2 classifiers, 30-m ranges independent of wind direction should be expected. A size of 2 ft^3, weight of 50 lb, and a power requirement of 40 w could well represent physical characteristics. These characteristics are determined primarily by the requirement for maintaining a vacuum rather than by other components of the system. Commercial, low resolution laboratory MS equipment can now be purchased for $5000 per unit. Development costs could be as high as $10M. Probably a development period of at least 5-8 years would be required.

Plasma chromatograph classifier

The plasma chromatograph (PC) is a relatively newly developed instrument with high sensitivity which can be used for the analysis of trace chemicals in air. The instrument can operate at atmospheric pressure which is a distinct advantage in comparison with the mass spectrometer which requires a high vacuum. In the simplest mode of operation, air is passed through a chamber containing a small nickel-63 radioactive source which emits low energy electrons. Normal components of the air are ionized to form positive and negative charged reactants. The presence of impurities or sample components in the sample air results in the formation of a stable, charged ion-molecule pair. The ion-molecule complexes then enter an electrical field region where separation of the various types of complexes based on mass occurs due to differences in mobility. The complexes arrive at a detector at different times, which is a function of mass. The intensity-time display has been termed a plasmagram.

The PC has undergone some evaluation for use as a military trace gas detector. Some tests have been run on use of the instrument as a vehicle detector. Detections were made probably as the result of organometallic complexes in exhaust. No information is available on the use of the

PC for vehicle classification. In its present stage of development, the PC is primarily a laboratory instrument for use as a research tool. Current costs range from $20K to $25K per unit. A considerable amount of study and development would be required to configure the PC for remote use in vehicle surveillance. Although the PC seems beyond the immediate scope of REMBASS applications, this item would seem to merit consideration for future application.

TRADE-OFF DETERMINATION

In previous sections on results of field tests, laboratory studies, and evaluation of chemical sensor concepts, information has been developed on operating principles, projected performance, physical properties, and development costs/time parameters for individual types of chemical sensors. These data are compared below in order to identify the most immediately promising approaches for REMBASS applications. Chemical detectors are considered separately from chemical classifiers.

Chemical Detectors

A general-purpose vehicle detector should respond to both gasoline and diesel vehicles. For this reason only those detectors potentially sensitive to particulates, nitrogen oxides, and carbon dioxide were included in the following trade-off determination. The flame ionization detector, which is sensitive only to hydrocarbons present in gasoline exhaust, and the flame photometric detector, which responds to sulfur in diesel exhausts, were eliminated for this reason. The thermal conductivity detector for analysis of hydrogen was also not considered since it is likely to be preferential for gasoline vehicles.

Projected performance

Projected performance parameters of the seven selected technical approaches are summarized in Table XIII. The risk indicated reflects a judgment of the amount of uncertainty that a given sensor can be configured to respond with a 90% detection probability to all vehicles at the detection ranges indicated. The various detectors are then ranked by consideration of performance and risk factors.

The condensation nuclei detector (CND) has demonstrated range superior to that of all other sensors. It is known to be responsive to particulate matter indicative of all vehicles. Due to relatively high performance and low risk, it is ranked one. The second ranked, alternative detector is the chemiluminescence detector (CID). The range given has not been proven in field tests so a medium risk has been assigned. However, the CID does respond specifically to nitrogen oxides. In contrast, the Honeywell ionization detector (HID) is rated third even though range is projected to be the same as that for the CID. This distinction is made because the HID must be configured to respond to nitrogen oxides which involves a higher risk than for the CID.

The next three detectors are projected to have lower but similar detection ranges. Of these, the infrared absorption detector (IAD) has the least risk since it is known to respond to carbon dioxide given off by all vehicles. Here, the risk is in uncertainty in performance rather than in the the concept. The kryptonate detector (KD) has never been tested for vehicle detection but is being developed specifically for exhaust component monitoring. A high risk is involved since a substantial increase in sensitivity to nitrogen oxides of the existing prototype model must be developed before the concept would be useful. The electron capture detector (ECD) has not been demonstrated

Table XIII. Projected performance of chemical detectors.

Technical approach	Target	Range (m), 90% detection: Downwind: Open	Range (m), 90% detection: Downwind: Wooded	Range (m), 90% detection: Independent of wind direction (sensor array)	False-alarm rate/24 hr	False-alarm rate increased by	Limitations	Risk (low, med, high)	Rank
Condensation nuclei (CND)	Vehicle	400	100	100	Nil	Combustion source		L	1
Honeywell ionization (HID)	Vehicle	150	50	50	Nil	Combustion source		H	8
Surface adsorption (SAD)	Vehicle	30	30	30	Nil	Combustion source	Low range	H	7
Chemiluminescence (CID)	Vehicle	150	50	50	Nil	Combustion source		M	2
Infrared absorption (IAD)	Vehicle	75	30	30	Nil	Combustion source	Low range	M	4
Electron capture (ECD)	Vehicle	75	30	30	Nil	Combustion source	Low range	H	6
Kryptonate (KD)	Vehicle	75	30	30	Nil	Combustion source	Low range	H	5

nor is a model that is certain to be sensitive to nitrogen oxides available for testing. In this case high risk involves the validity of the concept as well as uncertainty in performance. The surface adsorption detector (SAD) is ranked last in the other alternatives for general-purpose detection. Although the technology exists, a SAD sensitive to carbon dioxide has yet to be assembled and evaluated in the field. In addition, the SAD projected range is lower than that for the other detector concepts.

Projected physical properties

Projected physical properties of the chemical detectors are given in Table XIV. These characteristics are given in terms of size, weight, power, and environmental restraints. With regard to temperature, extreme temperatures are likely to increase power requirements. Although most of the detectors could be designed to withstand normal temperature extremes under stable conditions, wide variation in temperature over short time periods may degrade performance. The current state of the art is illustrated by the nearest example of a given technical approach. The "other requirements" column indicates characteristics which could cause special logistical problems or limit the period of unattended use. The risk reflects uncertainty that the nearest example could be further developed into a detector with stated physical characteristics.

The SAD clearly would have superior physical properties in all respects. The low risk is assigned because similar types of SAD not sensitive to carbon dioxide with these characteristics are commercially available. Even though the CND is currently limited to operation at above freezing temperatures, it is rated second because of lower size and power requirements in comparison with the other remaining detectors. Since the CND has already undergone some development for military purposes, the uncertainty in stated parameters is low. The third choice HID is placed over the fourth choice ECD because of a lower risk, coupled with the ECD requirement for a special gas for operation. The remaining three detectors have similar characteristics. However, the IAD is placed fifth due to a somewhat lower risk. The KD is favored over the CID which requires oxygen gas for operation. Both the KD and CID are considered high risk items in comparison with the other alternative approaches.

Projected development time and costs

Development time and cost considerations are summarized in Table XV. In determining unit costs, an estimate based on experience in development of chemical agent detector systems coupled with available information on costs of current detectors was first made for production of 1000 units. To be consistent with USAMERDC estimates for higher production volumes of other detector concepts, costs for 10,000, 25,000, and 100,000 units were prorated at about 76, 68, and 60% of unit cost for 1000-unit production. Risk is a value judgment based on the uncertainty in unit and development costs, and time. In comparing detectors, unit cost was considered more important than development costs.

The development time and costs are similar for the CND, HID, and SAD. The risk involved in each of these cases is low. The SAD is ranked number one over the CND followed by the HID, based primarily on projected unit costs. The ECD is rated fourth in comparison with the HID due to a higher risk in conjunction with higher development costs and a longer development period. A medium risk is also associated with the remaining CID, IAD, and KD alternatives, which have higher but similar development time and cost requirements. The IRD, KD, and CID are ranked five, six and seven, respectively, based on unit costs.

Table XIV. Projected physical properties of chemical detectors.

Technical approach	Size (in.^{3})	Wt (lb)	Power (w)	Environment (can withstand) Temp °F	Humid	Alt	Shock	Nearest example	Emplacement	Other requirements	Risk (low, med, high)	Rank
Condensation nuclei (CND)	75	2.5	2	+32-+150	Yes	Yes	Moderate	MS Personnel Detector	Hand, air	Water	L	2
Honeywell ionization (HID)	200	2.5	4	–20-+150	Yes	Yes	Moderate	Air Force Multiagent Detector	Hand, air	Radioactive source	L	3
Surface adsorption (SAD)	5	0.2	2	–20-+150	Yes	Yes	Severe	CRREL Prototype, commercial monitor	Hand, air Ballistic	No pump	L	1
Chemiluminescence (CID)	200	2.5	4	–20-+150	Yes	Yes	No	Commercial monitor	Hand	Oxygen gas	L	7
Infrared absorption (IAD)	200	2.5	4	–20-+150	Yes	Yes	No	Commercial monitor	Hand		M	5
Electron capture (ECD)	200	2.5	3	–20-+150	Yes	Yes	Moderate	Commercial monitor	Hand, air	Radioactive source, possibly special gas	M	4
Kryptonate (KD)	200	2.5	4	–20-+150	Yes	Yes	No	Commercial prototype	Hand	Radioactive source	H	6

Table XV. Projected development time and costs of chemical detectors.

Technical approach	Development Costs ($M)	Development Time (yr)	Cost based on these quantities 1,000	10,000	25,000	100,000	Production schedule	Risk (low, med, high)	Rank
Condensation nuclei (CND)	3	3	300	220	205	180	9 mos ARO*	L	2
Honeywell ionization (HID)	3.5	3	600	480	410	360	9 mos ARO	L	3
Surface adsorption (SAD)	3	3	100	77	68	60	9 mos ARO	L	1
Chemiluminescence (CID)	5	4	2,000	1,510	1,360	1,200	9 mos ARO	M	7
Infrared absorption (IAD)	5	4	1,500	1,150	1,015	900	9 mos ARO	M	5
Electron capture (ECD)	4	4	600	550	400	360	9 mos ARO	M	4
Kryptonate (KD)	5	4	1,600	1,150	1,015	900	9 mos ARO	M	6

*After receipt of order.

Trade-off ranking

The individual rankings of the detectors based on performance, physical properties, and development parameters are summarized in Table XVI. In addition, an overall risk ranking is assigned which reflects the uncertainty that a detector with stated characteristics and performance could be developed for the time and costs given. In establishing the overall rating for the various technical approaches, primary consideration was given to performance, unit costs, development time and costs, and overall risk. Physical characteristics were normally considered only when they were of extreme significance, or when comparing two approaches with otherwise similar characteristics.

The CND is rated one in comparison with other detectors, based on distinctly superior performance, moderate costs, and low risk. The SAD is rated second despite the fact that this detector is projected to have the lowest detection range and a medium risk. This placement was made primarily on the basis of lowest unit costs coupled with the recognition that the SAD would have physical characteristics which most nearly meet REMBASS requirements. The HID, which is rated third, is characterized by moderate performance, development characteristics, and physical properties at medium risk. It was also taken into consideration, as discussed later, that this particular detector shows potential for use in vehicle classification. The CID was placed fourth. In this case, high risk, and high development and unit cost factors are partially offset by projected performance. The IAD, ECD, and KD are difficult to rate since generally unfavorable characteristics dominate each case. Of these, the IAD was placed fifth since it should exhibit the highest performance at the lowest risk. The ECD is favored over the KD primarily due to cost considerations.

Table XVI. Trade-Off ranking of chemical detectors.

	Trade-Off ranking				
Technical approach	Performance	Physical properties	Development time and cost	Overall risk (low, med, high)	Overall rating
Condensation nuclei (CND)	1	2	2	L	1
Honeywell ionization (HID)	3	3	3	M	3
Surface adsorption (SAD)	7	1	1	M	2
Chemiluminescence (CID)	2	7	7	H	4
Infrared absorption (IAD)	4	5	5	M	5
Electron capture (ECD)	6	4	4	H	6
Kryptonate (KD)	5	6	6	H	7

Chemical Classifiers

Vehicle classification using chemical sensors can only be evaluated at this time at the level of discriminating between diesel and gasoline powered vehicles. For this purpose, combination of two sensors each specific for a different exhaust component seems to be the most promising approach to development of a classifier, all factors considered. Some of the classifier concepts described previously were eliminated from the trade-off determination based on a preliminary evaluation. Most of the remaining concepts involve sensors which individually show potential for a vehicle detector. One exception to this is the flame ionization/flame photometric classifier. Although neither of these sensors would respond as a general-purpose detector, combination of the two is useful for classification since the flame ionization detector is sensitive to gasoline exhaust while the flame photometric detector indicates diesel exhaust. Another exception is the mass spectrometer. This sensor is not competitive with the other concepts at the classification level under consideration. However, the mass spectrometer should remain under consideration since it would be a leading contender in future attempts to classify vehicles at a more detailed level.

Projected performance

Projected performance data for the various technical approaches are given in Table XVII. Risk indicates uncertainty in the technical approach as well as the projected range. The highest rating was given to the CND/HID classifier. Detection should be reliable based on CND performance. However, there is a moderate risk since the HID must still be configured to be specific for either gasoline or diesel vehicles. The HID combination was ranked second even though range equal to the CND/HID is expected. This rating was made based on a higher uncertainty in total reliance on the HID concept.

Table XVII. Projected performance of chemical classifiers.

Technical approach	Target class	Range (m) Downwind Open	Range (m) Downwind Wooded	Range (m) Independent of wind direction (sensor array)	% Target detection goal	% Correct class goal	Limitations	Risk (low, med, high)	Rank
Condensation nuclei/ Honeywell ionization (CND/HID)	Vehicle (all/diesel/gas)	150	50	50	90	90		M	1
Dual Honeywell ionization (HID)	Vehicle (all/diesel/gas)	150	50	50	90	90		H	2
Honeywell ionization/ surface adsorption (HID/SAD)	Vehicle (all/diesel/gas)	30	30	30	90	90	Low range	H	6
Condensation nuclei/ surface adsorption (CND/SAD)	Vehicle (all/gas)	30	30	30	90	90	Low range	M	5
Dual surface adsorption (SAD)	Vehicle (all/gas)	30	30	30	90	90	Low range	H	7
Flame ionization/flame photometric (FID/FPD)	Vehicle (diesel/gas)	100	30	30	90	90	Low range	M	3
Mass spectrometer (MS)	Vehicle (all/diesel/gas)	100	30	30	90	90	Low range	H	4

The third alternative based on range is the FID/FPD. In this case, the medium risk reflects uncertainty in performance range since both detectors have been included in field tests, and are known to show preference for gasoline and diesel vehicles, respectively. The fourth ranked MS has not undergone any testing. However, the concept is believed to be feasible based on results of laboratory studies on molecular analysis of exhaust gases supported by other information. Range is projected to be the same as for the FID/FPD classification but a higher risk is involved for the MS classifier. In making this rating no consideration is given to the possibility that the MS could classify vehicles in more detail than would be possible using the other technical approaches. The remaining three classifier concepts have the lowest ranges. The CND/SAD has the lower risk because the response of both detectors is known, and detection reliability is high due to the CND; it is rated as the fifth alternative. The HID/SAD is placed above the seventh ranked SAD primarily on the basis of risk. Although the risk is high in both cases, the odds favor the HID/SAD due to the larger number of detector response options available for configuration as a classifier.

Projected physical properties

Projected physical properties for each type of classifier are given in Table XVIII. The dual SAD classifier would clearly be superior to all other alternative approaches in terms of physical properties alone. The CND/SAD device ranks second primarily on the basis of size even though operation is currently limited to above-freezing temperatures. The third ranked HID/SAD classifier would be almost three times as large. In both cases, addition of the simple SAD should allow for ease in design and configuration for development. Except for power requirements, the physical properties are essentially the same as those for the CND and HID alone. The larger dual HID is selected as the fourth alternative. In comparison to the fifth-place CND/HID, it is composed of common units which will reduce problems of training and maintenance as well as permit ease of development. The current HID is already configured in a dual mode for detection of chemical agents. It can also be used over a wider temperature range. The FID/FPD classifier was ranked below other concepts with less desirable characteristics since a higher risk is involved. Special fuel gas is required which is an additional complicating factor. In operation, a flame must be maintained in producing a response although the FID and FPD could possibly have a common burner jet. The various parameters for the MS classifier are quite speculative so a high risk is involved. The values given for the MS are clearly not competitive with those of the other concepts.

Projected development time and costs

Projected estimated development time and cost are shown in Table XIX. Unit costs per 1000 units are estimated based on experience with costs for chemical agent detectors coupled with information available on costs for current models of individual representative detectors. Costs for 500-unit production are assumed to be the same as for 1000-unit quantities. To be consistent with USAMERDC estimates of cost reduction for larger orders, unit costs for 10,000-and 25,000-unit production were assumed to be 76% and 68% of unit costs for production of 1000 units. Risk indicates the degree in uncertainty in development for the time and costs stated.

The dual SAD classifier has a distinct unit cost advantage over all other concepts, and a lower development cost. Consequently, this alternative is ranked over the CND/SAD alternative even though a higher risk is involved. However, the CND/SAD has lower production and unit costs at a lower risk than the third-place HID/SAD unit. The dual HID and CND/HID are ordered consecutively in lower priority because of increasing unit costs. The sixth ranked FID/FPD classifier has higher unit and production costs, and a longer development time. The MS classifier ranked last has the highest costs and longest development time coupled with a high risk.

Table XVIII. Projected physical properties of chemical classifiers.

Technical approach	Size	Wt (lb)	Power (w)	Environment (can withstand) Temp °F	Humid	Alt	Shock	Nearest example	Emplacement	Other requirements	Risk (low, med, high)	Rank
Condensation nuclei/ Honeywell ionization (CND/HID)	275 in.^{3}	5	4	+32-+150.	Yes	Yes	Moderate	M8 Personnel Detector + Air Force Multiagent Detector	Hand, air	Water, radioactive source	L	5
Dual Honeywell ionization (HID)	300 in.^{3}	3	5	−20-+150	Yes	Yes	Moderate	Air Force Multiagent Detector	Hand, air	Radioactive source	L	4
Honeywell ionization/ surface adsorption (HID/SAD)	200 in.^{3}	2.5	5	−20-+150	Yes	Yes	Moderate	Air Force Multiagent Detector + commerical monitor	Hand, air	Radioactive source	L	3
Condensation nuclei/ surface adsorption (CND/SAD)	75 in.^{3}	2.5	4	+32-+150	Yes	Yes	Moderate	M8 Personnel Detector + commercial monitor	Hand, air	Water	L	2
Dual surface adsorption (SAD)	10 in.^{3}	0.2	3	−20-+150	Yes	Yes	Severe	Research sensor + commercial monitor	Hand, air ballistic		L	1
Flame ionization/Flame photometric (FID/FPD)	200 in.^{3}	5	3	−20-+150	Yes	Yes	No	Commercial monitors	Hand	Special gas	M	6
Mass spectrometer (MS)	2 ft^3	50	40	−20-+150	Yes	Yes	No	Commercial prototype	Hand	High vacuum	H	7

Table XIX. Projected development time and costs of chemical classifiers.

Technical approach	Development Costs ($M)	Development Time (yr)	Cost based on these quantities 500	1,000	10,000	25,000	Production schedule	Risk (low, med, high)	Rank
Condensation nuclei/ Honeywell ionization (CND/HID)	6	4	1,000	1,000	760	680	9 mos ARO*	M	5
Dual Honeywell ionization detector (HID)	4.5	4	750	750	750	510	9 mos ARO	M	4
Honeywell ionization/ surface adsorption (HID/SAD)	5.5	4	700	700	530	475	9 mos ARO	M	3
Condensation nuclei/ surface adsorption (CND/SAD)	5	3.5	500	500	380	340	9 mos ARO	L	2
Dual surface adsorption (SAD)	4	3	200	200	152	136	9 mos ARO	M	1
Flame ionization/flame photometric (FID/FPD)	7	4	2,000	2,000	1,520	1,360	9 mos ARO	M	6
Mass spectrometer (MS)	10	5-8	5,000	5,000	3,800	3,400	9 mos ARO	H	7

*After receipt of order.

Trade-off ranking

The ratings for each technical approach in terms of performance, development time and costs, and physical properties are summarized in Table XX. In addition, an overall risk factor is assigned to indicate the uncertainty that an item with stated performance and physical characteristics could be developed for the time and cost given.

The dual HID classifier is ranked as the best technical approach. This classifier shows good performance at medium costs and a medium risk. The second ranked CND/HID has a higher performance rating but is more expensive and has less desirable physical characteristics. The third-choice dual SAD classifier is rated the lowest of all alternatives in terms of performance. However, this disadvantage is countered by significantly lower costs and much more desirable physical characteristics in comparison with the other approaches. The fourth ranked CND/SAD unit shows low performance but is generally desirable in terms of costs, physical properties, and overall risk. The HID/SAD classifier has lower performance, higher costs, and poorer physical characteristics at a higher risk than the CND/SAD alternative. The FID/FPD classifier is ranked third in terms of performance but has been assigned to sixth place due to generally unfavorable characteristics in other respects. The last ranked mass spectrometer classifier is a high-risk item. It has an anticipated moderate performance but also has the least favorable development and physical property characteristics.

Table XX. Trade-Off ranking of chemical classifiers.

	Trade-Off ranking				
Technical approach	*Performance*	*Physical properties*	*Time and cost*	*Overall risk (low, med, high)*	*Overall rating*
Condensation nuclei/ Honeywell ionization (CND/HID)	1	5	5	M	2
Dual Honeywell ionization (HID)	2	4	4	M	1
Honeywell ionization/ surface adsorption (HID/SAD)	6	3	3	M	5
Condensation nuclei/ surface adsorption (CND/SAD)	5	2	2	L	4
Dual surface adsorption (SAD)	7	1	1	M	3
Flame ionization/flame photometric (FID/FPD)	3	6	6	M	6
Mass spectrometer (MS)	4	7	7	H	7