Counter Proliferation

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Study Leader:
N. Lewis
W. Happer

Contributors Include:
C. Callan
J. Cornwall
S. Drell
R. Garwin
J. Kimble
S. Koonin
G. MacDonald
R. Muller
T. Prince
E. Williams
F. Zachariasen

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JASON
The MITRE Corporation
1820 Dolley Madison Boulevard
McLean, Virginia 22102-3481
(703) 883-6997

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N. Lewis, W. Happer, C. Callan, J. Cornwall, S. Drell, R. Garwin, J. Kimble, S. Koonin, G. MacDonald, R. Muller, T. Prince, E. Williams, F. Zachariasen

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This JASON report has been prepared in response to a request from the Defense Counterproliferation Initiative to comment on key areas of their program and to suggest the application of new technologies to key problems in the area of counterproliferation.

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Contents

1 EXECUTIVE SUMMARY AND RECOMMENDATIONS

1. Intelligence efforts should focus on humint collections as early as possible in the proliferation time line and should continue such efforts throughout the proliferation effort. In addition to the usually emphasized signatures that might characterize BW/CW agent manufacture or storage facilities, intelligence efforts should also focus on the establishment of a sustained program in boundary layer meterology and the signatures thereof.

2. Small, lightweight mines should be considered as a means of active intervention before delivery of CW/BW stockpiles.

3. A layered battlefield CW/BW alert system should be developed, emphasizing generic broad area alerts that would then cue agent-specific analytical instrument packages which are highly mobile and are deployed at the troop level. Such a broad alert might include LIDAR to indicate the presence of an aerosol cloud, or an "electronic canary" to alert systems that a CW/BW attack has been initiated. Instruments that perform specific identification of the agent of concern should be deployed widely but separately from these generic alert systems.

4. Relatively immobile BW/CW analysis platforms like HMMWV's should be augmented with, or replaced by, extensive deployments of post-mounted instruments and/or instruments mounted on inexpensive, short range UAVs.

5. Consideration should be given to BW agent detectors that first select suspicious particles from the background according to their size characteristics and then perform analysis and agent identification on a single selected particle.

6. Although LIDAR methods appear promising to provide specific identification of the use of CW agents on the battlefield, we recommend that such a system be developed in conjunction with a generic alarm system, so that it can be cued by the generic sensors in a timely fashion to interrogate a suspicious cloud or artillery burst.

7. Characterization and analysis of the levels of natural and anthropogenic background fluorescence should proceed before significant investment is placed in development of a functional LIDAR system whose purpose is to ascertain whether a suspect cloud contains BW agents; attention should also be devoted to the robustness of such a system if the agent is encapsulated.

8. Improved weather models seem to offer promise to narrow down the very conservative "keep-out" zones in the soldier's field manual, but should not be relied upon to predict precisely the path of an individual cloud in the battlefield.

9. A high-level oversight committee, that reports to an appropriate official in DoD, should provide long term stability and a corporate memory to the DCI to enable it to pursue sensible counterproliferation efforts from administration to administration.

2 INTRODUCTION

In an address to the United Nations in September 1993, President Clinton identified countering the proliferation of weapons of mass destruction (WMD) and their delivery systems as one of the U.S.'s highest priorities. Additionally, during this address, the President stated: "If we do not stem the proliferation of the world's deadliest weapons, no democracy can feel secure." [1]

In response to this concern, the DoD has established a Defense Counterproliferation Initiative (DCI). [2] The DCI is designed to deal with all aspects of proliferation. In the timeline of a proliferation effort, the DCI focus starts with technical means to detect the initial development of weapons of mass destruction, then emphasizes the development of technologies to address signatures of a proliferation program, and finally addresses issues related to a response to the military use of WMD. [2]

This JASON report has been prepared in response to a request from the DCI to provide comments on key areas of their program. The JASON study group was also requested to suggest the application of new technologies to key problems in the area of counterproliferation.

This report is divided into nine sections. We initially provide some background and context for this JASON study within the context of the Deutch report describing technologies needed for an effective U.S. counterproliferation effort. [1] Since the Deutch report placed its highest priority on means to detect the use of, and deal with use of, biological weapons, the first section of this JASON report assesses the threat scenarios involved in the actual use of biological weapons.

The subsequent sections of this report follow the timeline of a hypothetical proliferation effort. This timeline is divided according to the maturity of development and deployment of the WMD. These sections contain some potentially new approaches for consideration in the DCI management and also contain recommendations concerning the effectiveness of ongoing technologies in specific aspects of the counterproliferation effort. The JASON study group was also asked to make specific comments regarding a list of proposed technological solutions supplied by the national laboratories to address various DCI problems, and they provided this feedback in both oral and written form to DCI staff during the course of the summer study. The final section of the report contains conclusions and recommendations for action under the DCI.

2.1 DoD Counterproliferation Initiative

We first advance useful working definitions of the terms of interest. In our context, nonproliferation refers to preventative measures that are taken to preclude a commitment to militarize WMD. Such efforts include export controls, diplomatic efforts, pressures of world bodies, sanctions against violators, and the like. These types of diplomatic efforts have traditionally been used to discourage the proliferation of nuclear weapons, but have recently gained increasing importance with respect to addressing the proliferation of chemical and biological weapons. Relevant treaties and/or international agreements to assist such diplomatic efforts include the NPT (nuclear proliferation treaty), the BWC (biological weapons convention) and the more recent CWC (chemical weapons convention).

Given this definition of nonproliferation, counterproliferation then logically would deal with the realization that non-proliferation will not be 100%

effective. Counterproliferation would thus refer to the development of a program to thwart weaponization of, prevent use of, and function militarily in response to, WMD. This is the primary basis of the DoD DCI effort, although the DCI also includes a DoD component to assist treaty negotiation and verification efforts of the State Department and includes some efforts to develop technological indicators of an emerging commitment by a proliferator to develop a WMD program.

It should be realized that it is unlikely that any set of technological tools can stop a determined proliferator from successfully pursuing and developing a WMD capability. For instance, the ability to develop WMD capabilities in the biological arena has become dramatically easier with recent advances in commercial biotechnology throughout the world. In addition, in some countries, there is an apparently increasing acceptance of the use of chemical weapons, with little worldwide outcry to discourage further development and/or use of such military tools. In view of this reality, the DCI program should be designed, in our opinion, primarily to accomplish two goals. First, the DCI should emphasize the development of a suite of technical means and intelligence sources designed coherently to determine with high confidence, at the earliest stage possible, that a nation is pursuing a vigorous commitment to develop a WMD program. Early warning might then possibly allow use of diplomatic steps to discourage the nation from developing a fully mature WMD program and from weaponizing its chemical, biological, or nuclear materials. Secondly, the DCI should emphasize battlefield warning and identification technologies that can reliably provide alerts in the eventuality that BW and/or CW weapons have been used on the battlefield. This is an area where technical means are greatly lacking, and where investment is likely to pay off with a useful system to enhance readiness and performance on the battlefield. The other goals of the DCI, including functional kill of underground facilities, passive defense methods, etc. are also important within the general goals of dealing with the eventuality of proliferation of WMD to countries with unfriendly (or worse yet, irrational), military policies towards the U.S. and its allies, but work in these areas is not likely to have the technological cost/benefit leverage of the two highest priority items.

2.2 Background

The Deutch report compiled a list of priorities that form the basis for the DCI program. [1] The highest priorities were: BW warning and defense, and obtaining improved technical capabilities to locate and kill underground structures. Note that this report did not prioritize items in order of their importance to an overall counterproliferation program, but established priorities in terms of value added for additional funding relative to ongoing efforts in the various DoD and DOE laboratories.

During our study, the JASONs heard briefings on the DCI program from the Office of the Secretary of Defense, DSWA, DARPA, Sandia, CBDCOM, USG, LLNL, Los Alamos, and the Special Operational Forces. We were also informed of the threat scenario for use of biological weapons that has led to its placement as the highest priority on the DCI. In response, the Army is developing the BIDS (biological integrated detection system), DSWA is working on improved weather prediction algorithms, DSWA and Sandia are developing programs to deal with functional kills of possible weapons storage and deployment facilities, and the DOE and Army laboratories are pursuing ongoing programs with lidar-based remote sensing capabilities for battlefield warning of BW/CW use. Our comments on the threat scenario, and an evaluation of the opportunities for individual technologies to contribute to an effective overall DCI program in these areas, are described below and comprise the main thrust of this report.

3 THE BW THREAT SCENARIO

3.1 Generic Threat Scenario

The oft-presented threat scenario for use of biological weapons is presented schematically in Figure 3-1. [2] This displays the area that can potentially be threatened by one crop duster dispersing a "generic" payload of anthrax or other related biological weapons. The swath is seen to cover a significant area relative to the size of a moderately large country, such as Saudi Arabia. The wide coverage is obtained because as little as 10^4 inhaled spores of anthrax is a lethal dose, and there are 10^{12} spores/kg of anthrax. This threat clearly poses a very serious problem to conventional military operations, and it is possible that large numbers of military and civilian personnel could be harmed or killed if no effective warning or countermeasures could be taken in response to such an attack.

3.2 Assessment of Threat

At first glance, this threat seems overwhelmingly frightening. However, there are several issues regarding the use of BW that must be considered in determining the viability of this threat in a specific "real-world" military scenario. We provide these comments to provide perspective with respect to the realities of widespread BW use in the near future.

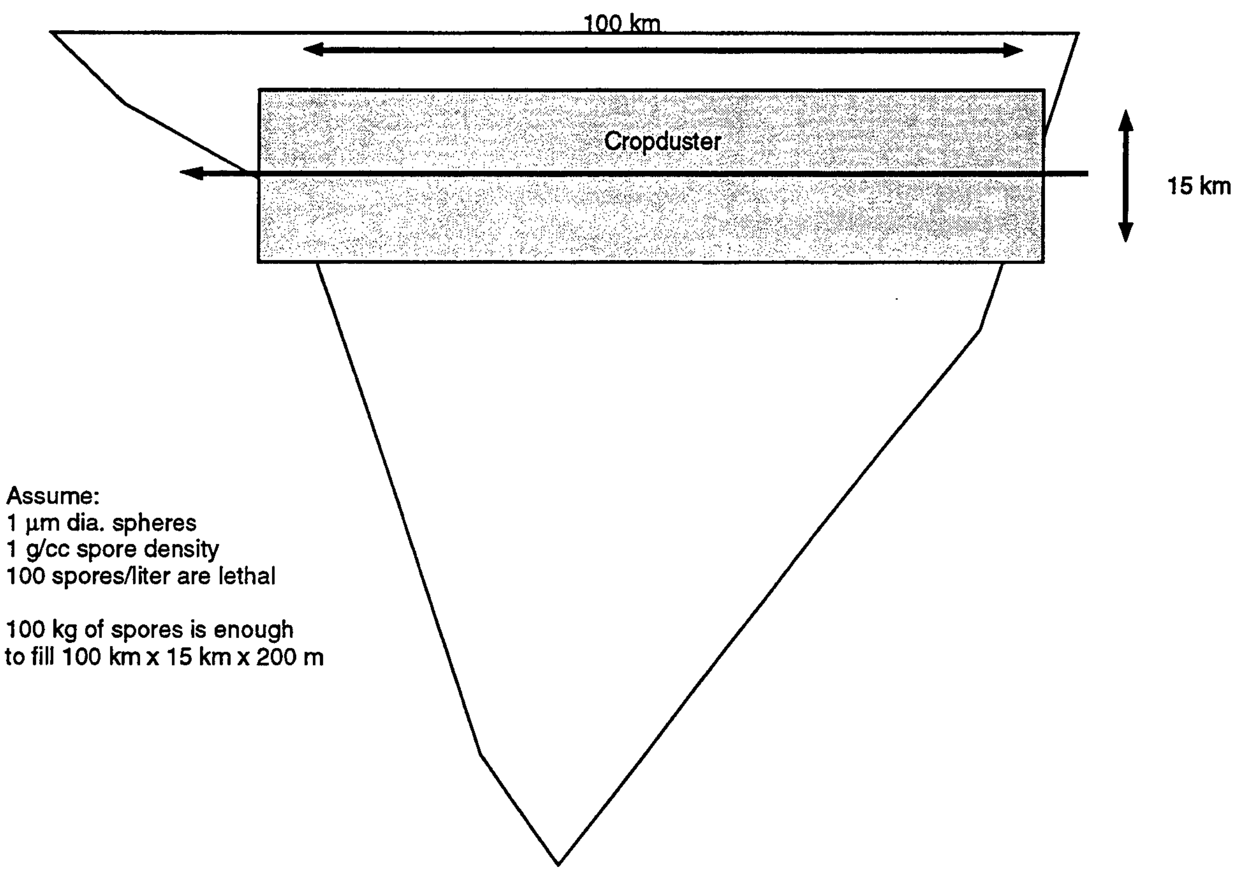

Figure 3–1. BW Threat

3.2.1 Why Has There Been So Little Use of Biological Warfare?

From the beginning of recorded history, armies have been ravaged by typhus, influenza, malaria, plague, and other diseases. Some 20 million deaths resulted from the influenza pandemic of 1918–1919. Such sobering casualty figures have led many to fear the intentional use of biological agents as weapons of mass destruction. However, instances of biological warfare are remarkably few, and the limited list would include for example, smallpox epidemics spread by intentionally contaminated blankets given to Indian tribes during the French and Indian War.

Less terrifying, but equally important for low-intensity conflict, is the possible use of infectious biological agents for domestic animals and crops. For example, naturally produced wheat-rust spores are blown thousands of kilometers from fall-sown wheat in Mexico and Texas to infect spring-sown wheat in the northern United States and Canada. The wind-born corn blight epidemic of 1970 in the U.S. wiped out 15% of that year's crop. Virulent, genetically engineered strains of plant pathogens could be used to wipe out the main food crops of unsophisticated opponents.

Better understanding of the nature of pathogens and their vectors has greatly diminished the military significance of naturally occurring disease. However, the same sophistication has increased concern that biological warfare could be added to weapons of mass destruction. Many countries, the U.S. included, have performed research on pathogens of humans, domestic animals, and crops. However, in spite of the great sums invested to develop modern methods of biological warfare, it has still not been much used, if at all. Thus, it is worth pausing to consider some of the reasons which may have deterred the use of biological weapons.

3.2.2 Slow Action

Living biological agents require an incubation time of many hours to days to produce symptoms. Thus, they are of no use in a fast-moving battle. Accidents like the release of anthrax spores at Sverdlovsk in 1979 produced relatively few cases of pulmonary anthrax, resulting in approximately 68 deaths in a city with a population of about million. Even in the most severely affected parts of the city, only a small fraction of the citizens were affected, and the initial symptoms developed over a period of days to weeks. This is the most striking difference between biological warfare with infectious agents relative to that with non-infectious biological toxins like botunlinin or rapidly acting chemical agents like nerve gas. Even if a BW capability were developed for anthrax, for example, and it were successfully delivered and caused to infect a large number of troops, detection of the attack by sensors would afford ample opportunity to prevent casualties by prompt treatment of those exposed to the spores; more importantly, military operations could still continue after such an attack. This stands in contrast to an attack with nuclear weapons, for example, which is fast-acting and which promptly destroys both people and property. Since use of BW would likely prompt nearly immediate, serious retaliation to prevent any further use of such weapons, it is likely only to be used by a desperate enemy faced with an otherwise unacceptable defeat.

3.2.3 Panic on the Home Front

Fear of biological warfare is so profound that one could hardly use such weapons without careful inoculation, training, and reassurance of one's own forces and population. It seems unlikely that such preparations could be kept secret. If one's own forces were not convinced of their safety in the event of a biological attack on an enemy, the use of biological warfare might do more harm than good.

3.2.4 Uncertain Delivery

Biological agents are usually dispersed as an aerosol. Local weather conditions, the wind direction, the stability of the atmosphere, precipitation, etc. determine the effectiveness of biological agents or whether they can be used at all. "The wind bloweth where it listeth", and there is always a possibility that biological or chemical agents will drift back over friendly forces and civilians. Chemical weapons have the same problem.

3.2.5 Retaliation

A powerful enemy can be expected to retaliate in unknown ways in response to a biological warfare attack. As a hypothetical example, an anthrax attack by Pakistan against India might be answered by retaliation in kind, since India is as technologically sophisticated as Pakistan. However, if severe (hundreds of thousands) of casualties were caused by the biological agents, Pakistan would have to anticipate possible retaliation with chemical or nuclear weapons.

The only uses or suspected uses of biological or chemical weapons since World War I have been by a more advanced country against a technologically primitive opponent, for example Italy against Ethiopia, Egypt against Yemen, Iraq against Iran, and perhaps North Vietnam and the Pathet Lao against Hmong tribesmen. Thus, Pakistan would be much more likely to use biological warfare against tribal rebellions in Baluchistan than against the Indian Army.

3.2.6 War Crimes Trials

Since there are treaties against the use of biological and chemical weapons, those responsible for their use would have a reasonable chance of being punished for war crimes in the event that war was lost.

These comments are provided because it is relatively easy to be alarmed by the swaths presented in a BW threat such as Figure 3-1. However, the realities are that for the reasons presented above, in our opinion BW is unlikely to be used in a battle against the U.S. in the near future. We will nevertheless, proceed below with the assumption that they might be used, and will discuss the technical means to detect their proliferation, detect their use, and defend against their use in battle.

4 INTELLIGENCE INDICATORS OF A WMD PROGRAM

4.1 Intelligence Indicators of a BW Program

As pointed out above, early indications of a WMD program afford a useful opportunity to exert diplomatic pressures on the proliferator. Based on the material presented to the JASON study group there appears to be no purely technical means by which a BW manufacturing program can be detected with certainty, much less geolocated with respect to pinpointing the actual production or storage sites. The required quantities of BW are readily manufactured using computer controlled, sterilized fermenters that are available on the open market. Using such equipment, a kilogram of anthrax, for example, could be manufactured within a few days, or at most, a few weeks of time. The cultures are readily available from the American Cell Type Culture for anyone who has a legitimate need to be working with them, i.e., to develop a vaccine, for example. The required initial quantities can, in fact, be obtained for as little as $50. After the cell cultures have been obtained, only standard fermentation equipment, comparable in size, appearance, operations, and emissions to a microbrewery, would be needed in order to obtain a militarily significant quantity of BW.

In principle, DSWA analysis (such as polymerase chain reaction, PCR, as proposed by a national laboratory for counterproliferation analysis) might, with a suitable sample collection scheme from areas close to a production site, reveal the presence of anthrax, for example. However, the significance of this finding is questionable because anthrax is indigenous to large areas of some countries (in cattle, for example). A more sophisticated analysis might search for DSWA signatures of the more particularly virulent strains of anthrax, although again there are so many different possible types that could be used that such a search would likely have limited value unless a definitive match was made with a very uncommon, virulent, form of anthrax. At present and in the near future, there is no obvious technical method by which BW facilities or BW production in militarily significant quantities could be robustly detected.

Because the BW production problem is so difficult to address with technical means, we instead discuss some other, perhaps more robust, intelligence indicators of a BW program.

4.2 Intelligence Indicators Of A Research Program On Boundary Layer Meteorology

A detailed knowledge of meteorological conditions and an ability to predict wind fields over a period of hours are absolute prerequisites to the confident use of chemical and biological weapons. Unexpected wind shifts can alter the affected population from enemy to friend. Convective activity can result in the dispersion of the agent to concentrations lower than that required to affect an enemy adversely. Indeed, chemical warfare during World War I stimulated research into boundary layer meteorology in Britain (G. I. Taylor), in Germany (Prandtl), and in Russia, France, and the United States.

We expect that countries planning to use chemical and biological weapons would conduct research on boundary layer conditions peculiar to their climatic and geographic setting and, if possible, to those of potential enemies. The goal of the research would be to develop a reliable predictive capability for wind, temperature, and humidity fields.

4.2.1 Boundary Layer Characteristics

In laboratory hydrodynamics, "boundary layer" has a well-defined meaning. In the atmospheric context, it has not been easy to define precisely what the boundary layer is. A useful working definition identifies the boundary layer as the layer of air directly above the earth's surface, in which the effects of the earth's surface (friction, heating, cooling) are felt directly on time scales less than a day, and in which fluxes of momentum, heat, and matter are carried by turbulent motions on scales of the order of the depth of the boundary layer or less.

The turbulent nature of the atmospheric boundary layer (ABL) is one of its most conspicuous and important features. However, turbulence in the lower atmosphere differs, in two main ways, from most turbulence studied in wind tunnels. First, turbulence associated with thermal convection coexists with the mechanical turbulence generated by wind shear. Second, boundary layer turbulence interacts with a mean flow that is strongly influenced by the rotation of the earth.

Over land in particular, the structure of ABL turbulence is strongly influenced by the diurnal cycle of heating and cooling, and by the presence of clouds. Neutral flow, in which buoyancy effects are absent, is readily produced in wind tunnels, and may be closely approximated in the atmosphere in windy conditions with a complete cloud cover. An unstably stratified ABL occurs when strong surface heating due to the sun produces convection in the form of thermals or plumes, and when upside-down convection is generated by cloud-top radiative cooling. A stably stratified ABL occurs mostly, though not exclusively, at night, in response to surface cooling by long wave emission to space. The unstable ABL is characterized by a near-surface superadiabatic layer and a stable ABL by the presence of a surface inversion.

The top of a boundary layer in convective conditions is often well defined by the existence of a stable layer (capping inversion) into which turbulent motions from beneath are generally unable to penetrate very far, although they continually erode it, particularly where latent heat is released in rising elements of air. The height of this elevated stable air is quite variable, but is generally below 2 to 3 km. The top of the convective layer is often characterized by a sharp decrease in aerosol concentrations. Over deserts in midsummer, under strong heating, the ABL may be as much as 5 km deep, and even deeper in conditions of vigorous cumulo-nimbus convection. In stable conditions, the boundary layer is not readily identified, turbulence is much weaker than in the unstable case, and consequently the depth is no more than a few hundred meters at most. At night over land, under clear skies and light winds, the depth may be even smaller, perhaps no more than 50 to 100 m, and may be strongly influenced by internal wave motion.

4.2.2 Intelligence Indicators

Intelligence tipoffs of a boundary layer research program supporting possible biological and chemical weapons include the presence of trained personnel, the availability of certain instruments and platforms, and the conducting of field research programs.

A. Educational Facilities

A relatively small number of educational and research facilities concentrate on boundary layer meteorology. Two leading schools of boundary layer studies are based in Australia, one at the National University in Canberra and Sydney University, and the other at the Division of Atmospheric

Research at the Commonwealth Scientific and Industrial Research Organization (CSIRO). In the United States, the National Center for Atmospheric Research has a strong program in boundary layer meteorology, working in collaboration with the Meteorological Wave Propagation Laboratory, Environmental Research Laboratories, NOAA, in Boulder. In addition, the University of Wisconsin at Madison and Pennsylvania State University have had active educational programs. In Great Britain, work is centered at Imperial College, London, and Cambridge University. In the Netherlands, Delft Technical University hosts a boundary layer program. Historically, the Soviet Union has been a player in boundary layer research since World War II at the Institute of Atmospheric Physics in Moscow and the Institute for Atmospheric Optics at Tomsk. It is less clear what are the current educational facilities in Russia for training researchers in boundary layer meteorology. The presence of foreign nationals at any one of the above research institutions could be a tipoff of a country's interest in the subject.

B. Instruments

Many of the instruments used in the study of boundary layer meteorology are also instruments that would be employed in general meteorological programs. Instruments for the measurement of temperature (thermometers), humidity (hygrometers), wind velocity (anemometers), and air pressure (barometers) are all commonly employed and widely available commercially.

Vertical variation of the various fields is an important determination in boundary layer research. The vertical variation can be obtained by conventional Rawinsonds, which are employed on a routine basis by meteorological stations around the world. However, detailed determinations of the turbulent fluxes require platforms of one sort or another.

A mast, upon which instruments can be placed at a variety of heights, typically is 10 m to 50 m. Sometimes scaffolding is used to erect a short tower. A mast is relatively inexpensive, and can be erected with simple equipment. Because of its limited height, it is primarily used for surface layer measurements. Sensors are often placed closer together at the bottom of the mast than at the top because the profiles of temperature, wind, and humidity vary logarithmically with height. Such masts can be easily transported and erected for a field program and then dismantled when the experiment ends. Wires carry the signals down the mast to a data logger or a data trailer located close by.

For continuing experiments at a permanent or semi-permanent site, tall towers have been constructed. For example, the Boulder Atmospheric Observatory tower in Colorado, about 25 miles east of the Rocky Mountains, is 300 m high. Occasionally, existing television transmitting towers are instrumented. Towers are particularly useful for studying night-time and early morning layers that are shallow.

The towers are large structures, with built-in elevators and many support guy wires. Because the tower is a large, it disturbs the flow close to and downwind of it. For this reason, towers have large horizontal booms that project away from the tower at different heights and upon which the sensors are mounted. This gives the towers a highly distinctive appearance. At each height, there are often booms projecting in two or three different compass directions, with the expectation that at least one of the booms will be pointing in the appropriate direction. Permanent or semi-permanent buildings house the communications, data logging, maintenance, and computer facilities that are sometimes built near the tower.

In addition to towers, a variety of balloons are used to obtain vertical structure observations. A kytoon is an aerodynamically shaped, helium-filled plastic balloon that is tethered by a winch on the ground. Instead of being blown downwind by the wind, the shape allows it to soar upward like a kite. In a typical application, a sensor package is suspended a short distance below the balloon on lines other than the tether line. To make measurements at a variety of heights, the winch is used to draw in or feed out more line, until the desired height is reached. The balloon is kept at each height of interest for 5 to 30 minutes to get a statistically stable sample before changing its altitude. Also, the balloon can make measurements while rising or descending. In some cases, the instrument package sends its signals down electrical wires attached to the tether cable, while for other kytoons, a transmitter radios information to the ground. Tethers on the order of 2 km are available. Kytoons are much more portable than tall towers, and can be easily used at temporary field experiments, but unfortunately they are limited to light winds.

Masts, towers, and kytoons are sure indicators of boundary layer research programs. Their measurements may be supplemented not only by Rawinsonds, but also by aircraft flights.

In recent years, classical techniques of boundary layer research have been augmented by the use of remote sensors of various forms. Remote sensors are radars, sodars (sometimes called acoustic sounders), and lidars. Various pulse-Doppler radar systems have been employed for obtaining new profiles in the boundary layer. Radars depend both on the index of refraction variations as well as particulates for returns. A typical meteorological profiler used in boundary layer research might have an average power of 1.5 kW operating at 33 cm with a range of 10 km and using a 10 m antenna. Such a profiler can obtain the vertical distribution of wind using particulates as the scattering medium, and operates at wavelengths of 3 m to 0.86 cm. In recent years, plume diffusion has been studied by systematically observing chaff contained within a plume. [3, 4] This type of experiment would be of particular interest for biological and chemical warfare applications.

Sodars depend on an audible "beep" of sound generated by powerful loudspeaker horns. The return sound is usually focused on a parabolic dish into a sensitive microphone that serves as the detector. To reduce the amount of ambient background noise entering the system, shelters and acoustic screens are usually erected around the dish microphone receiver, or else the receiver is placed in a hole below ground. Sodars obtain backscatter from the index of refraction irregularities. Sodars routinely detect the interface at the top of the mixed layer, using variations between the cooler mixed layer air and the warmer temperature inversion air capping the mixed layer. Reach by sodars is usually limited to about 1 km, with a system operating between 1 and 3 kHz.

Lidars use laser light, which is scattered off air molecules, cloud droplets, and aerosols in the boundary layer. The returned light is collected in a telescope and focused on a photon multiplier detector, after which it is amplified, digitized, and correlated. The boundary layer often is characterized by a higher concentration of aerosols than the free atmosphere. This can easily be tracked by lidar (JSR-93-310, "LIDAR").

A research program supporting chemical and biological warfare will also involve routine monitoring of the atmosphere, which would be indistinguishable from conventional meteorology. In addition, however, a potential user of these weapons would wish to carry out programs in a variety of geographical locations, as well as at different times of day and different seasons. Such a program should readily be identified by the use of towers, masts, and balloons, such as the kytoons. A program would undoubtedly employ radars of the meteorological profiler type and, in addition, might employ sodars and lidars.

4.3 Intelligence Indicators Of A CW Program

Unlike BW production efforts, which are difficult to distinguish from legitimate biotechnology industries, CW programs generally employ characteristic factories and equipment of a type and scale that are not typically used in the manufacture of common industrial chemicals. These fairly large facilities often have significant levels of unique emissions that might afford specific signatures of a CW program. In addition, much larger quantities of CW agent are needed to comprise a militarily significant threat, and thus there are opportunities for detection of a CW program during various stages of agent manufacture, agent storage, and weapons testing.

The emissions from a CW plant could, in principle, be detected by either point or remote sensors. An accompanying JASON study on unattended ground sensors (JSR-94-140A "Unattended Ground Sensors for Counter Proliferation Applications") has suggested routes by which small, low power covert chemical sensor suites might be designed to provide intelligence information on whether a suspect facility is a site of CW proliferation activity. Remote sensing technologies, primarily using differential absorption (LIDAR) methods, have also been assessed in the JASON report JSR-93-310 "LIDAR". These are discussed in some further detail below in view of their proposed emphasis in the DCI. Under some optimistic circumstances and with a lack of attention to plant emission controls, laser-based remote sensing methods can yield valuable information regarding the status of a CW program and regarding the quantity and identity of agents being manufactured at a site of interest. In more demanding instances, remote sensing will be less useful, and other signatures, such as the boundary layer meteorology program discussed above, must be relied upon.

Conventional imagery will also be useful in gaining information about a suspect CW facility, due to the large scale needed to manufacture militarily significant quantities of CW agents. However, such imagery will likely need to be cued by humint and/or by another sensing method in order to focus on the site of interest. Thus, imagery should be viewed as a complimentary method to remote spectroscopic or point sensors, as means of locating and interrogating CW facilities, especially those that are concealed after construction by natural or artificial features.

4.4 Whistleblowers and Humint

The importance of whistleblowers and humint should not be underemphasized in establishing the presence of a WMD program. In fact, such sources might be essential to obtaining information on a BW program. Although this is "low-tech" in that it relies on culturing encounters with specific people in a WMD program, it is very high leverage and should not be ignored in the effort to find a technical solution to the problem of proliferation detection.

5 INTERVENTION BEFORE USE

We now assume that the proliferator has been detected and that diplomatic pressures have failed to persuade the country to abandon its efforts, or that the proliferation effort has gone largely undetected to the point of weaponization or near-weaponization of WMD. The question in a counter-proliferation effort then becomes whether there are steps that can be taken in the form of a pre-emptive strike to intervene with the proliferator in a fashion that does not involve significant collatoral damage to civilians. The lack of collatoral damage is especially important for nuclear reactors, but also is pertinent to stockpiles of chemical and/or biological weapons that might have been discovered but have not yet been used. We address some ideas for intervention before WMD use in this section.

5.1 Intervention into the Production of Special Nuclear Materials

We first discuss methods to stop the production of a nuclear reactor without causing the release of radioactivity. The goal is to halt the production of special nuclear materials, especially plutonium, with little or no risk to nearby civilian populations or to the surrounding territory.

To accomplish this task, we take advantage of the fact that the radioactive material (in virtually every reactor that would be of interest) is in an isolated section of the reactor, which we refer to as the "primary section". There is another part, equally vital to the operation of the reactor, that we call the "secondary section", and which contains no significant radioactivity. If we can destroy or otherwise stop the operation of the secondary section, then the entire reactor (and the production of nuclear materials) is brought to a halt. The effort required to rebuild the secondary can be substantial, and if it is rebuilt it can be attacked a second (or third) time.

We do not assume that the primary section has substantial "containment" capabilities against the danger of a melt-down. For example, the experience at Chernobyl shows that many reactors do not have well-designed containment. Most reactors that lack containment still, however, have isolated primary sections, which are separated from the secondary in order to minimize the every-day release of radioactivity. An isolated primary is all we need for safety against the release of dangerous radioactivity, even if there is little containment built around the reactor itself.

5.1.1 Relevant Aspects of Nuclear Reactors

Nuclear reactors can be optimized for the production of plutonium and other radioactive isotopes, or for the production of power. In both cases they produce a great deal of heat. In Figure 5-1 we show a typical configuration for a nuclear reactor, in which we have emphasized the elements that contribute to heat removal.

Heat is produced in the nuclear reactor core vessel, and is carried off by fluid (typically gas or water) in the primary cooling loop to the heat exchanger. The fluid in the primary loop is exposed to intense levels of neutrons, and so becomes radioactive itself. We have indicated this in the diagram by asterisks(*); note that the level of radioactivity in the primary cooling loop is much lower than in the reactor core vessel itself (as indicated schematically by the lower density of asterisks in the primary cooling loop). The heat exchanger is designed to transfer the heat to a non-radioactive substance, and to provide isolation for pipes that enter the primary vessel

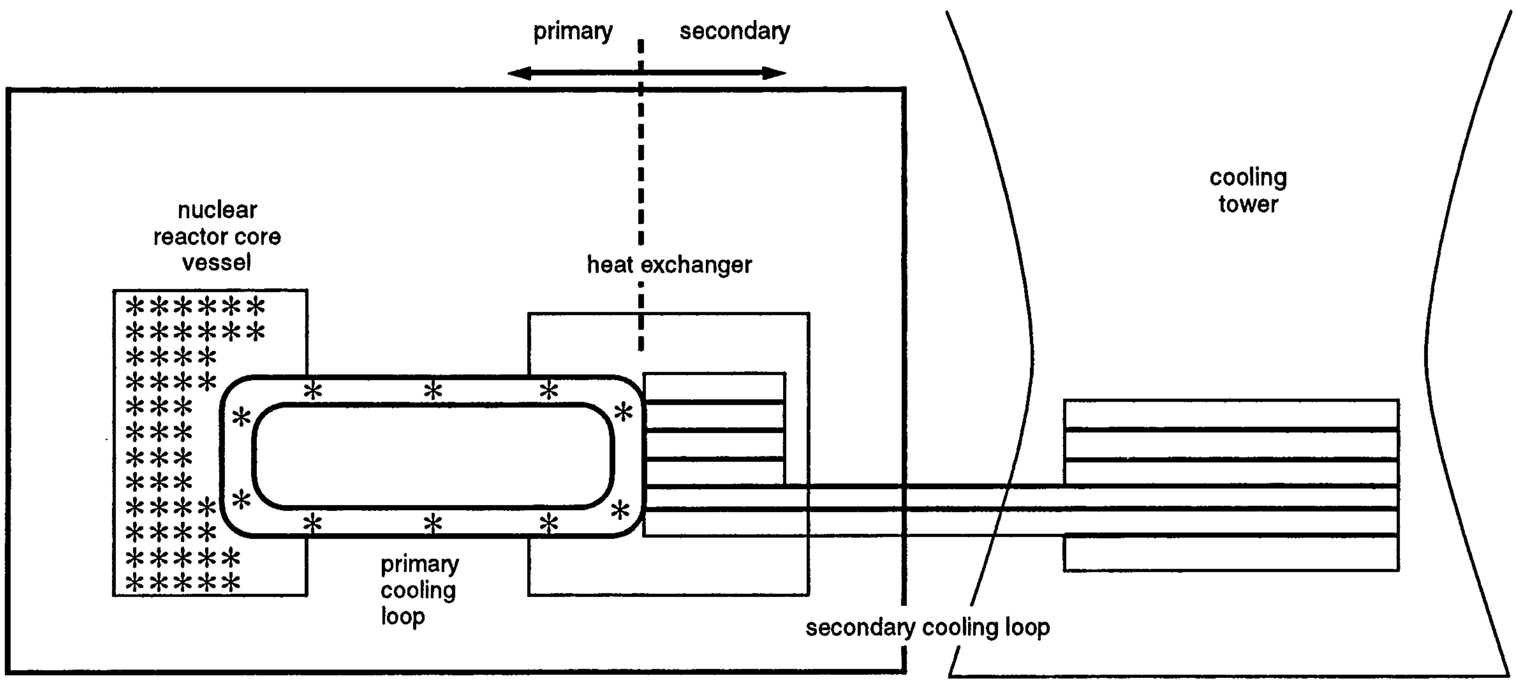

Figure 5–1. Relevant aspects of nuclear reactors.

itself. In a power reactor, the heated water (or steam) in the secondary is used to drive a turbine. But in any kind of reactor, most of the heat will be waste, and must be disposed of. Typically 80% or more of the power produced in a 25 MW plant is waste heat, and this heat must be eliminated either through the use of rivers or other large bodies of water, or through the use of cooling towers. To remove 20 MW of power by evaporation requires 40 tons of water per hour.

A. Scenario 1: Attack the Cooling Tower

For the purposes of counterproliferation, the most vulnerable section of the reactor is the secondary. Unless the secondary is functioning, the reactor cannot operate, because it must get rid of the waste heat. For a reactor with a cooling tower, the attack is particularly easy; destroy the tower using a smart bomb or a cruise missile. The danger of release of radioactivity is quite low; in fact, the primary danger will most likely be from a mis-aimed bomb or missile that strikes the reactor building itself. Once the tower is destroyed, operators or automatic systems will sense a rise in the temperature of the primary loop and will shut down the reactor by inserting the control rods. If this is not done, then the fuel in the primary will be damaged by thermal distortion of the fuel elements and the support structure. The reactor cannot be operated if such damage occurs, and it will be very difficult to repair, so when the temperature rises in the primary loop the chain reaction will be shut off.

Reactors are designed to be able to cope with the loss of their secondary cooling. For a medium-sized reactor, if the nuclear reaction is shut down (insertion of control rods) within a few minutes of the loss of the secondary cooling then no damage will occur to the primary. Larger 1000 MW reactors have special emergency cooling systems. There is no realistic danger of a metldown as long as the primary remains intact. The usual meltdown scenarios (Chernobyl, Three-Mile Island) occur from the sudden loss of the primary coolant, not of the secondary cooling system.

Of course, we must be cautious. Before any attack is made on an existing reactor, the general conclusions of these arguments should be confirmed by a review of the specifics of the reactor. However we believe that the results of that review would confirm, in most cases, the statements that have been made above.

Although the cooling tower can be rebuilt, it cannot be rebuilt secretly. The cooling tower has the job of releasing large amounts of heat to the atmosphere, and that prevents it from being hidden. Cooling towers cannot be placed underground, unless there are very large vents that would yield detectable clouds of water ("steam"), and such underground cooling systems can be put out of commission by the destruction of the vents. Once the cooling tower is rebuilt, it would be once again vulnerable to attack by cruise missiles or smart bombs.

B. Scenario 2: Special Forces Attack

If one can get access to the reactor, even if for only a few minutes, then a much more devastating attack can be made. In addition to destroying the cooling tower, the target will now include the heat exchanger. This can be attacked by clogging the pipes in the secondary loop of the heat exchanger, or perhaps even by bursting them. No significant radioactivity will be released as long as the primary loop is undamaged. The heat exchanger is a much more difficult system to repair, particularly if an embargo against the country inhibits the importation of spare parts.

To clog the heat exchanger, material can be inserted into the secondary loop. It will be necessary to bypass filters that are used to remove dust and debris. The exact nature of the action will depend on the design of the heat-exchanger, however a few general principles apply. In most cases, the piping in the heat exchanger will be narrow, to facilitate the transfer of heat (large surface-to-volume ratio). So objects (e.g. balls of glue) inserted into the secondary cooling system are most likely to get caught inside the heat-exchanger. In addition, if the reactor has recently been running, then the heat-exchanger is hot. This feature can be used, for example, by inserting material that decomposes when it is heated. If such a material is used, then it may not be necessary to bypass the filter system. Another possibility is a thermosetting plastic or chemicals that react with hot water to produce thick foams.

The attack against the heat exchanger has the additional feature that it will work against a reactor that has no cooling tower, e.g. one that uses river water for cooling. Such systems may have much more elaborate filtering systems, and it may be necessary to bypass them (except with the heat-sensitive decomposition method described above). An attack against the heat exchanger has the disadvantage that it requires direct access to the reactor, if only for a short time.

The National Research Council has produced a report on the vulnerability of nuclear reactors to terrorist attack. We have not attained a copy of that report, but it may contain a list of vulnerabilities that we have not considered.

5.2 Neutralizing Chemical and Biological Storage Areas

5.2.1 Introduction

In this section, we discuss a method to "neutralize" a facility that contains storage canisters or production equipment for chemical and biological warfare. We imagine that we have located a warehouse (or underground building, or other covert facility) containing lethal chemical or biological warfare materials. We want to render the material unusable by the enemy who has stored it there, but do not want to bomb this facility for fear of collateral damage, perhaps to a nearby population. The method must be effective but also practical and long-lasting.

Imagine as our most difficult problem (but a realistic one) a large room containing a thousand 55 gallon drums filled with phosgene. Assume that we have brief access to the warehouse, say, 10 minutes, through military or special forces action. What can we do?

One suggestion (that does not satisfy our criteria of practical and long-lasting) that was advanced by a briefer is to deliver several hundred tons of glue or slime and spread it over and through the drums. We think that transporting the large amount of material makes the approach virtually unusable, and that the clean-up of the material would not seriously impede the enemy.

5.2.2 Proposed Solution: "Can Opener" Limpet Mines

The most effective neutralization method, given the scenario described above, that we have found is the implanting of a new kind of mine. Each of these mines need only be a few ounces in weight; we will conservatively assume that each weighs a half-pound. One soldier could carry up to forty of these. The effectiveness of these small mines comes from the leverage they obtain by being placed on the drums themselves. Their job is simply to release the dangerous material (chemical or biological) from a single drum if the mines are moved or disturbed.

The mines have magnets and/or contact cement to hold them to the drums. Given access to the storage area, the soldier places the mines on a selection of the drums. If the drums are densely packed, then he places the mines on the drums that are on the outside, i.e., the drums that would have to be moved first.

A conceptual design for a mine is shown in Figure 5-2. The mine is designed to blow a hole in the side or top of the drum, and to create enough of an internal pressure to drive out a significant fraction of the chemical material inside.

Of course we may not want to drive out much material; the goal of the mine is to create a disabling nuisance to the enemy, and that could be caused by the leakage of just a few ounces of chemical agent.

An alternative design would use a squib, an explosively-driven knife, to slice open the side of the canister. It might look like Figure 5-3.

The flat region above the knife prevents the knife from penetrating more than about 1 cm deep, so that the explosive energy of the squib drives the

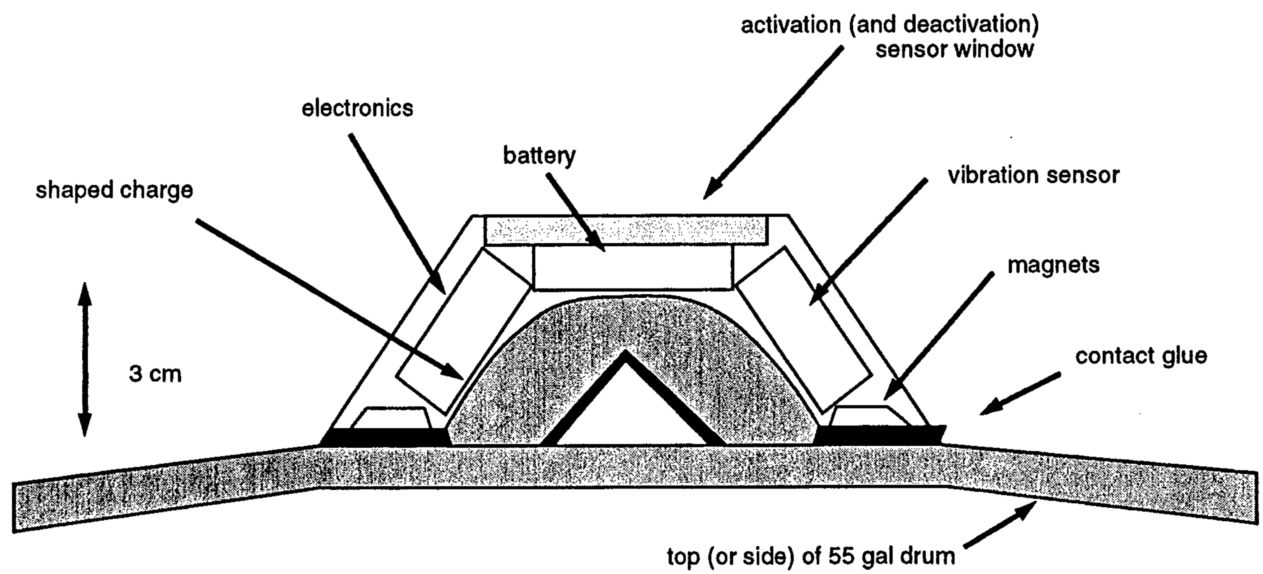
activation (and deactivation)
sensor window
electronics
battery
shaped charge
vibration sensor
magnets
3 cm
contact glue
top (or side) of 55 gal drum

Figure 5–2.

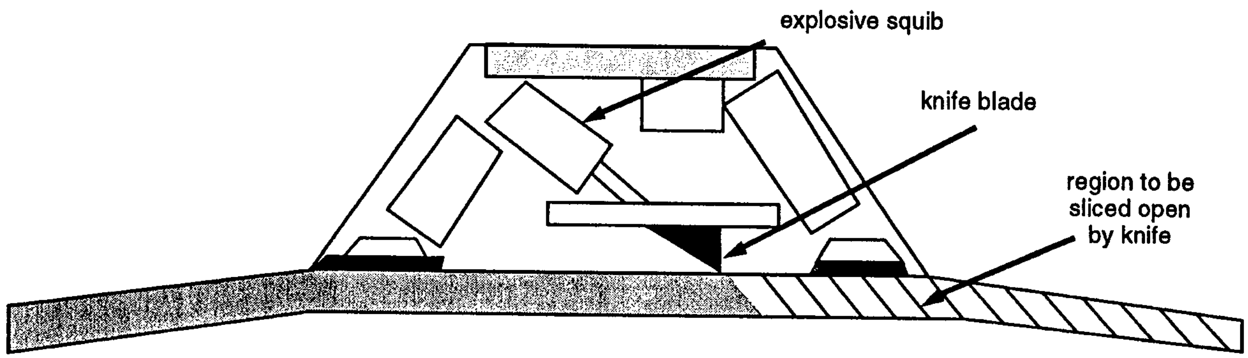
explosive squib
knife blade
region to be
sliced open
by knife

Figure 5–3.

knife blade along the surface of the can. This geometry is very similar to that found in the can opener of a Swiss Army Knife, except for the squib.

5.2.3 Activation and Deactivation

We have included in the diagram a sensor window to allow the mines to be turned on and off. Having such a feature will facilitate the placement of the mines by allowing them to be roughly handled until they are in place. Once the mines are activated, any strong vibration or attempt to dislodge them (or empty the canister) will send a vibration to the accelerometer that will trigger the explosion. All of the mines could be activated with one signal, but we might want to have different deactivation signals for each. This could be readily achieved through a public key/private key scheme in which the serial number on each mine is bar-coded onto the unit, and deactivation takes place only when the appropriate private key is entered into the deactivation unit by scanning the bar code on the mine. To prevent an exhaustive search for the key, repeated but unsuccessful attempts to deactivate the mines would cause them to trigger. The battery included in the mines would draw a very low current; its purpose is to operate the sensor circuit. A safety feature would deactivate the mines if the batteries ran low, but there would be tamper-proofing to prevent deactivation merely by removal of the batteries or tampering with the electrical circuitry.

The deactivation feature gives us the option of rendering the mines harmless at the cessation of hostilities. Care must be taken to make sure that the deactivation feature is not purposefully destroyed, e.g., by the enemy as he retreats from occupied land. Thus, for example, we might not want to use an infrared sensor (since it could be painted over) but we might instead use an acoustic sensor that is responsive to an encoded series of vibrations. It might also be possible to use a radio-frequency sensor.

5.2.4 Fratricide

Our overall goal in this exercise is to avoid the widespread release of toxic agents by making it likely that any disturbance will cause the release of a small amount of the agent. We presume that the enemy will try to remove at least one of the mines, or move one 55-gallon drum to a "safe" area. We would like that attempt to fail, resulting in the release of 55 gallons of toxic agent. However, we do not want a chain-reaction to set in, with the explosion of one mine triggering the explosion of every other mine in the storage area, for that could result in just the kind of death and destruction that we had hoped to avoid. This is the problem of "fratricide" and it has no obvious solution. We will suggest a few possibilities, although we do not feel that we have found the perfect solution.

1. Design the mine to produce a minimum of vibration. In this concept the eruption of one squib, slicing a knife several inches across the surface of a canister, does not trigger a mine attached to a nearby canister. This would take some experimentation, and it might prove to be impractical.

2. Include a spectrum of trigger criteria, with most mines requiring more than one trigger to be detonated. For example, among 40 mines, two might be triggered to explode as soon as they sense a sudden acceleration, a change in orientation, or an attempt to tamper. The others would simply begin counting. Some of the mines would explode after two such attempts; others would require three, four, or more. Of course the enemy would not know which were which. Warning signs explaining the system would be left behind so that the enemy would know

the dangers inherent in trying anything. This system would have the advantage that an accidental explosion or earthquake would not set off the entire inventory.

3. Just before a mine detonates, it emits an encoded "squawk" temporarily deactivating the other mines. Every mine would be capable of being temporarily neutralized by many different squawks, but no mine would accept the same squawk twice (this is to prevent the enemy from detonating one canister, listening to the squawk, and then duplicating it). We are uncomfortable with this approach, since we feel that there may be ways to fool it.

The mine system that we have described could be used in production facilities (e.g., large fermentation vats) and perhaps in munitions storage areas. The method is probably unnecessary for research areas, since they probably contain a small enough quantity of dangerous material that they could simply be destroyed.

Finally, we note that emplacement of smart mines similar to the ones we describe here could be used in many other military applications. For example, we recall the situation when the U.N. forces in Bosnia-Herzogovenia garrissoned Serbian artillery, but later had to allow the Serbs to recapture the weapons. It would have been possible to leave smart mines in the barrels of the guns if such mines had existed.

6 INTERVENTION BEFORE DELIVERY

Intervention before delivery, but after launch, of a missile containing WMD appears to be adequately addressed in the ongoing tactical ballistic missile defense program. Similarly, current US programs are also directed towards defeating a cruise missile attack, armed with either a conventional or WMD warhead. The study group did not review these technologies in the course of this work.

It should be noted that, with respect to active defense against a BW attack, the delivery vehicle is especially vulnerable. In times of conflict, a slow, low-flying crop duster flying either in, or slightly upwind of, territory under friendly control should command suspicion and should attract immediate attention, especially during special times at which the meteorology is favorable for a BW attack (night time, high atmospheric stability, low wind velocity, etc.). In fact, such an aircraft may be the most vulnerable aspect of a BW program, and is readily detected and defended against if one is actively looking for its presence.

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7 WARNING AFTER DELIVERY

7.1 Biological Integrated Detection System

The Army BIDS (Biological Integrated Detection System) consists of a collection of off-the-shelf biological detection instruments, both for specific and non-specific detection purposes. These instruments are mounted on a High Mobility Multipurpose Wheeled Vehicle (HMMWV) in a shelter designed to protect the crew from biological agents. The instruments to be included in the BIDS for general detection are an aerodynamic particle sizer, a flow cytometer, and a bioluminometer; for specific detection, the instruments will consist of an antibody-based threshold device and a "Sensitive Membrane Antibody Recognition Test" (SMART). [2] As new instruments are developed, they can be integrated into the BIDS.

The idea of mounting biological weapon detection systems of various kinds on a single platform is obviously a good one, it minimizes false alarms, allows for updating the platform with newer and better instruments, and can provide timely and useful information of an attack provided the platform is in the right area at the right time.

It is the idea of using a HMMWV as the platform for all of this which causes us concern. We wonder whether, given their limited mobility, it is feasible to have enough HMMWVs present over the entire area of concern to provide adequate coverage.

Various alternatives suggest themselves. One is to simply transfer the existing sensor package to a helicopter platform. This would be more expensive per unit, but given the large area which can be covered quickly the number of platforms would be much less. The blowers on the HMMWVs could clearly be eliminated since the helicopter motion in itself would be enough to generate sufficient airflow for enhanced detection sensitivity.

If one is willing to redesign the BIDS instruments, they could be very greatly reduced in cost, size, weight, and power requirements. Also, one could consider dispensing with the sensors used for specific agent detection and be satisfied with the information that "something bad is out there" which could be obtained from the general detection instruments.

Either of these changes in instruments allows a considerable number of new options for deployment, particularly if they are designed to operate autonomously, with remote communication, obviating the need for a crew which needs to be protected.

One could, for example, simply mount a set of instruments on posts a few feet off the ground, in a pattern at some distance in front of, and along the sides of, the troop units to be protected. The posts could be equipped with fans, at low power cost, to increase the air flow past the sensors and to achieve increased sensitivity. The exact spacing and pattern used would, of course, depend on the size of the protected area and on the location of troop units within it. The same thing could be done with tethered balloons. In fact, this deployment is not so different from using HMMWVs, given their low mobility, except for the numbers involved. Its main advantage is that it is unattended, and so avoids the problem of having to protect a crew.

Alternatively, the instruments could be placed on very small, cheap, short range UAVs which would be sent out periodically, as well as to sample suspicious looking clouds (among all the other clouds of dust which are generally an integral part of any battlefield).

In the schemes involving stationary sensors (posts or balloons), as stated above, the density and location of sensors must be determined by the geometry of the troop disposition to be defended. As an illustrative (and overtrivalized) example, suppose the defending troops are deployed in a line of length L. To be effective, the attacker must then spread his BW over a line of the same order, upwind from the defenders. As the BW clouds move with the prevailing wind, it may break up into several separate clouds, each of which may be much smaller than L. Therefore the sensor package, be it deployed on HMMVWs, posts, or balloons, would have to be spaced apart a distance of the order of the dimension of the subcloud. If the sensor package is mobile (really mobile–not like HMMWVs but on helicopters, UAVs, or in artillery shells) it must be deployed in a time short compared to the prevailing wind speed divided by the distance to the place where the BW cloud was laid down.

Neither of these requirements is very stringent, and neither requires a huge number of detection units.

7.2 A Layered Sensor Structure For BW/CW Warning

Given the wide variety of potential biological agents, and the possible variation in chemical agents, one important recommendation is that a first level warning system should not be based on specific detection technologies for a limited set of CW or BW agents, but should be a general purpose detection system for airborne materials that pose a significant threat to mammalian functions. After a general warning has been sounded, a more specific interrogation should then be performed to investigate the actual type of agent and to initiate the appropriate defensive actions to take in response to the attack. A schematic of this type of approach is laid out in Figure 7-1. This

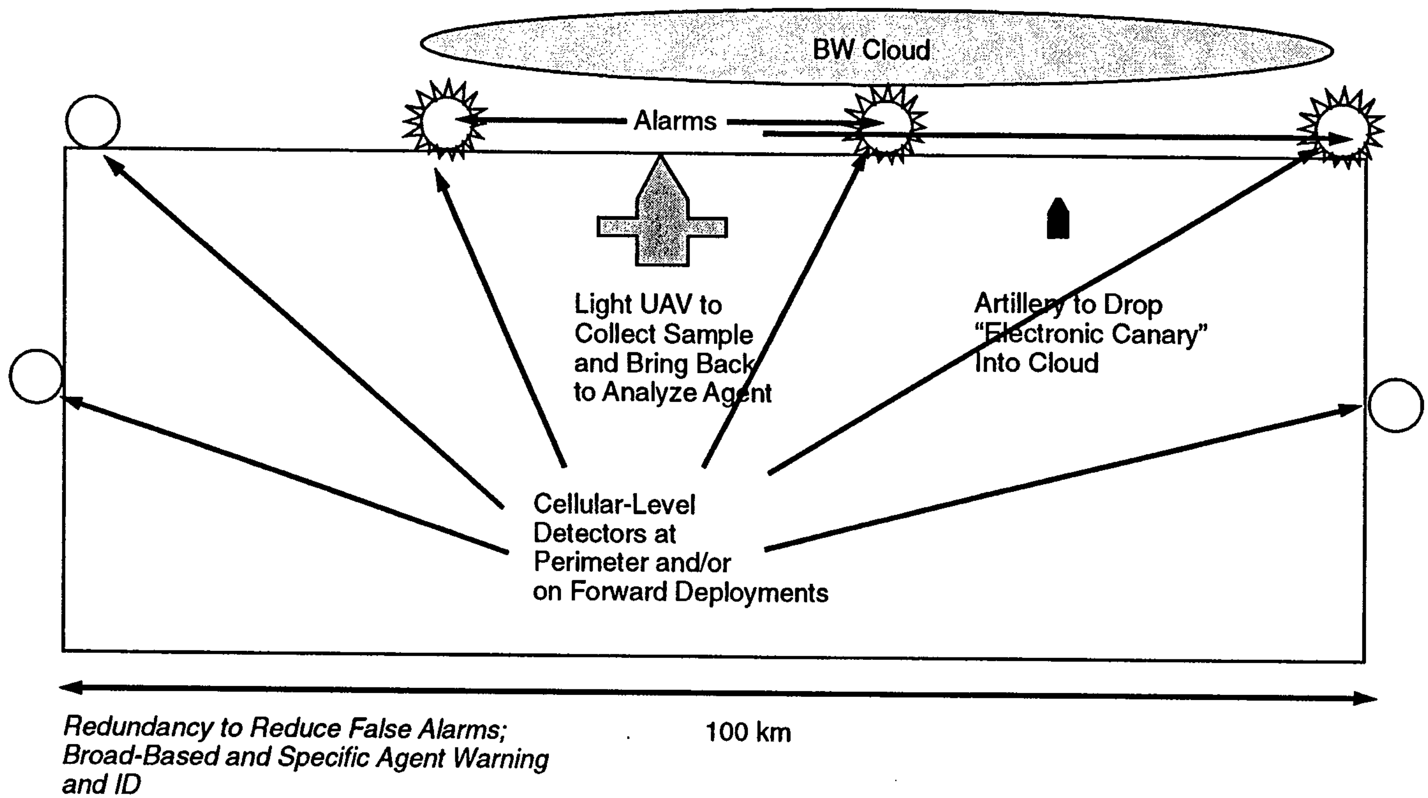

Figure 7–1. BW Battlefield Warning System.

type of perimeter-based general CW/BW alert system stands in contrast to most of the plans presented to the JASON study group that involved mobile vans, helicopters, or UAVs mounted with lasers, which are likely to be expensive, to have limited range, and to not be useful against all types of agents.

What one really wants as a first alert is an "electronic canary" which triggers an alarm when presented with any toxic substance higher than a prearranged natural background level. False alarms could be minimized by requiring that several alerts from differently located sensors be received within a given time frame; in fact, the sequence of such responses could be used to gain information on the cloud path and on the flight path of the delivery vehicle, to allow for a strike before its mission is completed and the agent fully dispersed along the intended path.

A microphysiometer that performs exactly this function has, in fact, been recently constructed. [5, 6] In this device, a light-addressable-potentiometric sensor (LAPS) device monitors cell growth rates with response times of less than 30 sec. Any CW or BW agent that affects the cell growth rate will yield a signal and could therefore be used to trigger an alarm. Thus, any nerve gas will inhibit acetylcholine function and will trigger a change in cell growth rate; similarly, the microphysiometer is sensitive to biologically-produced toxins. A similar cellular level approach seems warranted to detect viruses and bacterial agents, so that any source of BW or CW agent would yield an alarm in a small, inexpensive, low power sensor that could be deployed in times of conflict around the perimeter of an area under friendly control.

If a form of remote sensing were desired, for example if a suspect cloud were detected, then such a microsensor could be dropped into the cloud from a parachute or perhaps even launched as artillery. During its flight it could return signals on the composition of the cloud, and on whether descent through the suspect region indeed resulted in exposure to a high concentration of agent, which should be fairly easy to ascertain by a number of detection methods.

A suitable immediate deployment of this type of technology, which would not require any new biology/chemistry developments, would be to use the antibody-based "smart tickets" chemistries that are currently available as early warning systems. However, instead of manual use of these tickets, they would be deployed routinely throughout the battlefield and would be equipped with an electronic interface and with an automatic sampling mechanism designed to eliminate the need for manual intervention. The stability of the antibodies can be enhanced by only exposing the paper to the water before use; a paper tape roll running through rollers, much like that described in the JASON UGS (JSR-94-104) would seem quite suitable for such a system. The readout could be a simple light emitting diode array that was configured to detect a diagnostic colorimetric change that produced upon reaction of the chemicals in the paper with the CW or BW agent. These devices could be carried by troops and also could be planted around the perimeter, and upwind, from any people that one wanted to warn about an attack. Such a device would be low power and inexpensive to fabricate in large quantities. When combined with the microphysiometer, the combination would seem quite suitable for a distributed early warning system approach to the BW/CW attack issue.

7.3 Battlefield Detection of BW Agents With Micro-UAVs

After a generic BW/CW alarm warning has been triggered and troops alerted, subsequent actions and defense will require a specific identification of the agent used. For detailed analysis of samples and specific identification of agent type, the BIDS approach involving the use of various methods to detect and identify biological and chemical agents seems to make good sense. However, much of the complexity in the BIDS, its large size and power constraints, and its immobility, arise from two issues: the need to protect the operators from exposure to agent and the need to sense and identify uniquely very dilute concentrations of agent before they rise to levels sufficient to cause irreversible harm to troops in the vicinity of the BIDS unit. As we have seen, the early warning system need not provide unique identification, just generic information that "something bad to people is out there". Both of the other remaining requirements currently in the BIDS could be relaxed if a sample could be remotely collected and then returned for analysis at a "safe" site.

Since it is of the highest priority in detecting battlefield use of BW agents to do so before the agents descend on unprepared, unprotected troops or civilians, even a few minutes of warning time may be enough to take effective passive-defense measures. This might suggest that remote sensing of the contents of a suspicious cloud or aerosol is the most desirable technology. Unfortunately, for reasons discussed below at length, this is not likely to succeed given current technical approaches: lethal agent concentrations are low, natural backgrounds are high, and most specific BW agent identifiers can only be used in the laboratory. So we turn to another possibility, which is remote (up to distances of perhaps 10s of km) sampling and return of samples to field laboratories.

As a specific example, we will keep in mind anthrax, for which a commonly-accepted lethal air concentration is 100 spores/liter. Once some 10^4 spores are inhaled, they vegetate and within days produce lethal toxins. However, antibiotics administered within 24 hours of exposure will save a large fraction of the exposed (unprotected) population. So sampling and identification does not need to be instantaneous in order to defend with prophylaxis, but sampling should be fairly quick if one wishes to don protective gear before the suspect cloud drifts over the exposed population.

We suggest here an alternative, or at least complementary, system to the Army's BIDS. Consider the use of very small UAVs, really overgrown model airplanes, of a type used not only by the Israeli military but also in a mini-helicopter version by film and TV crews to get otherwise impossible overhead shots. Similarly, a micro-UAV could reach areas inaccessible to a HMMWV and could go more quickly to accessible areas.

This is not the forum to design such a craft in detail, but we will advance a few figures to demonstrate feasibility. The usual formulas for the lift force L and the drag force D of a subsonic aircraft are

$$L = \frac{1}{2}\rho v^2 S C_L \tag{7-1}$$

$$D = \frac{1}{2}\rho v^2 S C_D \tag{7-2}$$

where ρ is the air density, v the aircraft velocity, S the wing area, and $C_{D,L}$ the drag and lift coefficients. These coefficients will have values like $C_L \approx 1, C_D \approx 0.05 - 0.1$. Suppose the micro-UAV has mass M of 20 kg, and $S = 10^4$ cm^2. Equating L to Mg yields a velocity v and power P of

$$\begin{aligned} v &= \left(\frac{2Mg}{\rho S C_L}\right)^{1/2} = 20\text{m/sec} \\ P &= vT/n = \frac{1}{2n}\rho v^3 S C_D \simeq 400\ W \end{aligned} \tag{7-3}$$

where T is the thrust, and we have chosen a propeller efficiency n of 0.5. A flight time of 10^3 sec (range 10 km, reached in 8 minutes) takes only a few hundred gm of fuel. The payload would consist of an air sampler, a video camera and a link for guidance; it might weigh 2–3 kg. A sampler of effective sweep area 100 cm^2 would sweep 200 liters of air every second, or 10^4 liters/km. A one-km cloud of anthrax spores at a density of 100/liter would yield up to 10^6 spores in a sample.

One might worry about contamination of the plane after its fly-through (just as one would worry about contamination of a HMMWV conducting a sampling mission). One might minimize this concern by coating the plane's exterior surfaces with recently-developed non-stick coatings, [7] which work better than TFE because they are non-porous.

7.4 Fast Detectors For Chemical and Biological Warfare Agents

7.4.1 General Approach

With few exceptions, delivery of chemical and biological warfare agents will be in the form of an aerosol of particles in the respirable size range (1-7 μm), at a particle density capable of delivering a toxic dose within about 5 minutes. Based on the known toxicities of potential agents, rough estimates of the aerosol particle density in the event of an attack are approximately $10 - 10^5$ bacteria/m^3 for a biological attack, $10^5 - 10^9$ aerosol particles/m^3 in an attack using toxins, and $10^7 - 10^{10}$ aerosol particles/m^3 in an attack using chemical agents. An effective advanced warning system requires the ability to detect and analyze such aerosols in a background of dust, debris, and indigenous biological material and under variable meteorological conditions. As much of the background material is in the form of particles larger than the respirable range, a detector based on air sampling to allow a separation of particles of different sizes has many advantages over a remote detection system. Aerosol collectors which use aerodynamic principles to pass only particles in the respirable size range are readily available. [8] Once the sample has been limited to particles in the respirable range, the background material will include indigenous bacteria, some yeasts and fungi, and fine inorganic material such as coal fly-ash. The nature and concentrations of background particles in this size range have not been widely investigated. However, from the small number of studies available, it is clear that both bacterial and yeast concentrations are highly variable with season, ranging over at least 100-1000/m^3 for bacteria and 10-2500/m^3 for both yeast and fungi. [9, 10]

Once the majority of the background has been eliminated by size sorting, there are a large number of physical methods of analysis which can be used to classify the remaining aerosol particles. [11] The analysis can be performed on the aerosol particles one-by-one as they are collected. Commercially available optical particle counters, for instance, allow individual particles to be sampled at rates of approximately 10^5 particles/min. [12] The most powerful and straightforward analysis techniques are light scattering, optical and fluorescence microscopy, and multi-color fluorescence detection. Light scattering measurements at one or two angles are used in commercial instruments for size determination, however it is well known that variability in shape or refractive index can lead to errors. This is because the complex angular scattering which occurs in the Mie scattering regime (particle size comparable to wavelength of scattered light) is highly sensitive to these parameters. [13] A detector which took advantage of this property by measuring the full angular distribution of the scattered light might well be able to characterize certain types of agents, for instance anthrax spores, unambiguously.

Because most BW agents are expected to be delivered as aerosols in the 2–10 μ range, disruption of particles in this size range should significantly enhance the probability of prompt detection of the agent. Two mechanical processes that can be employed are milling and ultrasound. Of the two, milling is a straightforward process which can be used after initial particle-size filtering to break up the microcapsules and release the BW agent. For this reason, a milling device should be included whenever feasible in a biological detection system. Mechanical break-up will work on most types of microencapsulation processes, directly releasing the agent for shell-core, shell-matrix, and matrix structures, and providing enhanced release for solution-type microcapsule structures.

Another technique that is widely used in characterization of aerosol particles is optical microscopy. While microscopic analysis is most typically performed on particles that have been fixed onto a glass slide, dynamic measurements of particles in a flow stream are possible using video detection. Respirable particles such as bacteria approach the resolution limit of light microscopy, however they do have readily distinguishable shapes which would allow automated discrimination of biological from non-biological particles using standard pattern recognition approaches.

Still more detailed information can be obtained from the intrinsic fluorescence of the aerosol particles, which can be detected as a fluorescent image using fluorescent microscopy. [14] Both inorganic and biological particles have characteristic intrinsic fluorescence signals. In addition to fluorescent imaging, multi-color spectral analysis (i.e. detection of intensity at several different wavelengths) is a powerful technique for characterizing particles. [15] Detailed characterization of the optical properties of background aerosol particles and expected warfare agents may reveal that there are classes of agents for which physical analysis can provide unambiguous identification. Investigation of this possibility is worthwhile because physical analysis methods are more robust and possibly may be more readily adaptable to field conditions than chemical or biological sensors.

In cases where physical analysis cannot provide a complete identification, the analysis system will still be important as an early alert system to activate other more sensitive instruments, and as a basis for separating aerosol particles for different types of analysis. Categories of aerosol particles that are likely to need different treatment are encapsulated particles, bacteria, spores, and liquid aerosol droplets. Techniques of flow cytometry can be used to separate these categories once they have been distinguished by physical methods. [16] Subsequent analysis can be performed with great sensitivity and specificity, as described below.

7.4.2 Detection via Extrinsic Fluorescence

Great specificity and sensitivity can be obtained in detecting chemical and biological warfare agents by using an extrinsic fluorescing molecule which is designed to respond (by a change in fluorescence) to a specific biochemical reaction of the agent. An example of such a detection scheme is the fiber-optic biosensor, which has been developed for the detection of anticholinesterases (such as nerve agents). [17] In this sensor, a fluorescing molecule (fluorescein isothiocyanate) is bound to the enzyme acetylcholinesterase, and is then immobilized onto the outer surface of an optical fiber. The fluorescence of the molecule is measured by introducing light into the fiber, which excites the fluorophore on the fiber surface. A portion of the resulting fluorophore emission is trapped in the fiber and transmitted to a detector at the end of the fiber. Readily measurable fluorescent signals are obtained with only about 10^{11} fluorophores bound to the fiber.

Under normal conditions, when acetylcholine is introduced into the sensor, the hydrolysis of the acetylcholine by the enzyme results in a decrease in pH, which quenches the fluorescence on a time scale of minutes. If a binding agent which inhibits the acetylcholinesterase (an anticholinesterase) is present, then hydrolysis and the corresponding fluorescent quenching does not occur. The speed of response of the sensor, and its ability to discriminate between different types of anticholinesterases, both depend on the strength of binding of the anticholinesterase to the enzyme. Weakly binding agents will give a signal only when present in very high concentrations. For instance, the common insecticides malathion and palathion, which are not anticholinesterases, compete so inefficiently with acetylcholine for binding to the enzyme that they give no measurable signal even at milli-molar concentrations. In contrast, the enzyme can be sensitized by preincubation to provide sensitivity to the anticholinesterase paraoxon, which is a metabolic product of palathion, at the level of 10^{-8} M. [18] The nerve agents sarin, VX and soman are 50–100 times more strongly binding than paraoxon, so that detection limits well below 10^{-9} M should be achievable. Given the sample volume of the sensor (46 μl), this means that detection of nerve agent could be accomplished on only approximately 10 aerosol particles that have been collected into a 1 ml dilution volume. Working at higher concentrations of the sample will allow faster detection, but will also increase the possibility of obtaining a positive response from other chemicals, such as insecticides, which might be present in the environment.

The fiber-optic based sensor can in principle be used as the basis for fluorescence detection of other chemical agents, such as toxins. For each agent to be detected, a specific biochemical reaction must be identified to couple the presence of the agent to a fluorescent signal. Thus a suite of such biosensors can be envisioned as a method of providing broad-band sensitivity to chemical warfare agents. The potential difficulties which will arise in adapting such sensors to field use are the requirement of a supply of pure water for sample dilution, the short lifetime of enzymes even under carefully controlled conditions of temperature and chemical environment, the sensitivity of fluorophores to quenching agents such as iodine or molecular oxygen, or the presence of naturally occurring fluorophores in the sample.

For the detection of biological agents, e.g. bacteria or bacterial spores, immunofluorescent techniques can be used. This involves developing antibodies which are specific to the known biological agents, attaching them to fluorescing molecules, and developing an incubation protocol for attaching the antibodies to the agent. The fluorescent signals of the samples could then be measured either using fluorescence microscopy, or by using multi-color fluorescence spectroscopy. Individual bacteria can be tested using this method with the techniques of flow cytometry discussed above. A major difficulty in developing a successful field technique using immunofluorescence is the long time scale generally required for incubation (typically more than 15 minutes). The difficulties (listed above) of working with fluorophores are also present. In addition, working with antibodies requires careful maintenance of physiological conditions, although they are likely to be more robust than enzymes.

7.4.3 Physiological Sensors

Ultimately, one would like to have a broad band detector which responds with appropriate signal strength to the presence of any chemical or biological agent dangerous to human health, i.e., the analog of the miner's canary. The difficulty of finding such a sensor is exemplified by the efforts of the toxicology community to find replacements for animal testing. As discussed briefly above, one interesting approach to this problem is a newly developed instrument called the microphysiometer, which senses the biological activity of a small number (as few as 100) of cultured cells by monitoring the pH of the solution around the cells using a light-addressable potentiostatic sensor. [5, 6, 19] Under the normal operating conditions of the instrument, the cells are found to acidify their environment at a rate of about 10^8 protons-s^{-1}-cell^{-1}. The introduction of various biochemicals known to interact with receptors on the cells has been found to cause measurable changes in the rate of acidification on time scales of seconds to minutes. This suggests that it might be possible to design a detector for biochemicals of interest by using cells transfected with receptors that are known to bind those agents. The responses to various biochemicals of a number of different cells having different types of receptors have been tested in the microphysiometer in an attempt to understand how the acidification rate of the cell is linked to the receptor. At present, the understanding of the linkage remains incomplete even for the well-characterized receptors which have been tested to date. This means that it is not yet possible to predict the response of a microphysiometer-sensor based on a new cell/receptor combination. The response of the microphysiometer to activation of a given receptor must be tested on a case-by-case basis.

The application of the microphysiometer requires identification of a receptor which both binds the chemical of interest, and induces cellular response by the binding. If the microphysiometer gives a measurable response to stimulation of a given receptor, then its potential for detecting agents which bind to that receptor will be determined by the strength of binding. As an example, the nerve gases are known to bind strongly to one type of acetylcholine receptor (the M2 muscarinic type) at concentrations below the nanomolar level. [20] It is not reported whether this binding activates (rather than simply blocks) the receptor. If it does activate the receptor, then operating the physiometer with cells transfected with this type of receptor could result in a detector with response properties comparable in speed and sensitivity to the fiber optic fluorescence sensor. Since the physiometer has been operated successfully with a similar type of receptor (the M1 muscarinic type), the possibility that it could be used to detect nerve agents is not unreasonable.

The activity of the microphysiometer has been demonstrated with a range of receptor types, suggesting the potential for future development as a broad band sensor. At present it is far from ready for use as a field instrument due to limited understanding of its biological transduction mechanism, and the practical difficulties of maintaining the cultured mammalian cells which serve as its basis. However it is potentially sensitive to extremely small amounts of material (4 μl sample volume, and only 10^7–10^8 receptor sites, yielding an ultimate sensitivity at pico-molar levels), and has demonstrated very rapid responses to chemical agents. Finally, because of rapid developments in cellular biotechnology, it is reasonable to expect that dramatic improvements in the performance of the physiometer may be attained.

7.5 LIDAR for Battlefield BW/CW Warning and Identification of BW/CW Facilities

An alternate approach, and one being pursued vigorously by many laboratories, involves spectroscopic identification of BW and/or CW agents through laser probes such as LIDAR. Because this class of technology has received so much attention from the DoD and DOE communities, the opportunities and limitations of this technology are discussed at some length below. The comments on LIDAR are pertinent to its uses both in the battlefield and as a remote sensing device, as briefly discussed above in Section 3.3.

On the whole, LIDAR detection and identification of CW and BW agents remains problematic in almost all realistic scenarios, ranging in mission from WMD production to alert of WMD use in the battlefield. In many cases, such as the remote monitoring of a production facility by a satellite or aircraft, the concentrations of the signature chemicals are simply too small to be detected at standoff distances of 100 km given our sense of the likely problems with backgrounds, speckle, variability of atmospheric transmission, etc. However, beyond the issue of detection is the even more daunting problem of identification. Even if a spatially localized signal is detected via LIDAR methods, one will have measured a trace of absorption versus wavelength (probably with large error bars) resulting from an (unknown) admixture of chemical species. The task then becomes assigning a confidence level to a hypothesis concerning the presence or absence of a given toxic chemical, such as the nerve agent GB, which produced that absorption signature. In the case of BW, the absence of unique spectroscopic signatures associated with a production facility is an unresolved obstacle.

In the sections that follow, we elaborate the material that has led us to these conclusions. Subsections 6.5.1 and 6.5.2 are an assessment of technical material in a Battelle Report on LIDAR detection of CW that was briefed to the JASON study group by Dr.Joseph Leonelli. [21] In Subsection 6.5.3 we turn to the issue of LIDAR detection of BW, primarily within the context of a battlefield BW/CW attack warning system. Principal points of reference for our analysis of remote detection by laser ranging are the materials found in the cited reports [21]—[25].

7.5.1 Remote Detection of CW Production Facilities

As a starting point in an assessment of the prospects for the remote detection of a chemical weapons (CW) production facility, we refer to the relevant section of the Battelle Report, [21] where a model calculation is presented for the production and release of effluents from the Al Muthanna Site in Iraq. Some idea of the degree of difficulty of the task of standoff detection (at distances of order 100 km for either a satellite or a remote aircraft) is obtained by examining the estimated flow of toxic agents at the stack itself. For unscrubbed emissions of the nerve agent GB, the Battelle Report estimates a flow of 17 mg/s at a velocity of 18 m/s through a stack of diameter d = 0.45 m, leading to a concentration at the stack of about 1.5 ppm (6 mg/m^3). To determine the feasibility of detection by optical or infrared absorption, we employ the absorption cross sections shown in Figure 7-1 of the Battelle Report. For example, for an absorption cross section $\sigma = 2 \times 10^{-18}$ cm^2 (as would be appropriate to a DIAL system based on a CO_2 laser operating at around 10 μm), the fractional change γ in power for transmission directly through the effluent at the stack is given by

$$\gamma = \rho\, \sigma\, d = 0.003 \tag{7-4}$$

where ρ is the number density. This is a very small change to detect in a laboratory with a spectrometer, much less remotely at 100 km with diverse uncharacterized backgrounds.

Even more challenging is the task of detecting absorption in the plume itself. For example, this stack emission rate for unscrubbed GB emissions at roughly 100 m downstream produces at its peak a concentration of only 10 ppb (30 μg/m^3). For a measurement made across the approximately 40 m width of the plume having an average concentration of approximately 3 ppb (10 μg/m^3), the fractional absorption γ is only about 5×10^{-4}.

Apart from these specific estimates, a variety of meteorological conditions must be incorporated in order to arrive at column densities CL for viewing both at nadir and at a slant angle directly along the plume (for maximum absorption). Note that for a uniform concentration, the column density is simply the product of the mass density and the absorption path length D. With the absorption cross section expressed in units of m^2/mg (where for GB, $\frac{\alpha}{\rho} = \sigma = 10^{-3}$ m^2/mg = 2 $\times 10^{-18}$ cm^2 with σ equaling the absorption cross section, α equaling the absorption coëfficient and ρ equaling the mass density), the fractional absorption associated with single-pass propagation is then simply

$$\gamma = \sigma CL\,. \tag{7-5}$$

In the most favorable circumstance [case (i) with stable meteorological conditions and with slant viewing (along the entire length of the plume), and at an elevation of 35 m], a column density CL for unscrubbed GB emissions of 17 m^2/mg, corresponding to an absorption coefficient $\gamma = 0.02$ (that is, to a 2% change in power for single-pass absorption) is obtained. However, for less favorable conditions, the absorption coefficients for unscrubbed GB for slant angle viewing range from 0.004 [(ii) neutral meteorological conditions, elevation 20 m] to 0.001 [(iii) unstable meteorological conditions, elevation 20 m]. For nadir viewing (perpendicular to the length of the plume, as for an overhead satellite), the situation is even less encouraging with absorption coefficients corresponding to the three cases above of (i) 7×10^{-4} (ii) 1.4×10^{-4}, and (iii) 9×10^{-5}.

Thus, in order to use LIDAR to detect signatures of a CW production facility remotely, one must be able to measure reliably fractional changes in absorption at a level beyond 0.01 for the "best case" (stable meteorological conditions and optimum viewing directly along the plume). However, if the system is to be of wide applicability, fractional absorptions at a level beyond 10^{-4} must be measured accurately and reproducibly. Note that these estimates are based on the case of unscrubbed GB emission from a localized source at a rate of 1.7×10^{-2} gm/s (or 1.5 kg/day). Scrubbing would drop the emission rate roughly fifty fold, so that even in the optimum case with slant viewing, the absorption coefficient would be only 4×10^{-4}.

These estimates for absorption coefficients must be assessed in light of existing and projected measurement capabilities and in view of theoretical constraints. A detailed analysis of LIDAR for remote sensing was carried out by a JASON study group during the 1993 Summer Study (JASON Report JSR-93-310). Although that report was principally concerned with the detection of nuclear proliferation facilities, many of the analyses and conclusions are relevant to the current study (see in particular, Section 3 on Absorption

Measurements and Section 5 on Speckle and Twinkle Noise). Rather than repeat those arguments here, we focus instead on two simple considerations, one of principle and one of practice.

The issue of principle is that the noise in any LIDAR system is ultimately set by "shot-noise" from the finite photon flux. More specifically, if N_R is the number of returned and detected photons, then the minimum detectable absorption γ_{SN} (for an optically thin medium, $\gamma_{SN} << 1$) is simply

$$\gamma_{SN} \approx 1/(N_R)^{1/2}. \tag{7-6}$$

For a 100 mJ pulse of 10 μm radiation, with an overall transmission, remote reflection, and detector efficiency of 10%, and with a receiver of diameter 1 m for a target at 100 km, this leads to $N_R = 5 \times 10^7$, and hence to $\gamma_{SN} \approx 10^{-4}$. Improvements in sensitivity beyond this value, through use of successive pulses, come at best at a rate $1/n^{1/2}$, with n being the number of laser pulses. If in fact levels of sensitivity comparable to the shot-noise limit could be achieved, then one could be somewhat optimistic about the prospects for remote detection of CW production.

Unfortunately a number of factors conspire to degrade performance and to keep the actual minimum value of γ above the fundamental shot-noise limit (including speckle: see JSR-93-310). A particular issue of practice is the variability and lack of knowledge of the target background, which provides for reflection, and hence return, of the LIDAR signal. These uncertainties in the background will undoubtedly be a major factor limiting the sensitivity and will likely preclude levels of less than (optimistically) $\gamma = 0.01$ from being achieved. If this is the case, the LIDAR will be ineffective for the remote detection of CW production facilities.

Some sense of the nature of the difficulty is provided by data included in the work of Ben-David et al. [22] These data show the reflection of trees in two seasons and show fractional variability with wavelength of considerably greater than 1%. Likewise, data are included for the atmospheric transmission over 150 m $\times$ 2 (down and back) and show changes substantially above 1%. If a LIDAR system were to be deployed, then reflection and transmission coefficients for a host of environmental factors (soil types, man-made structures, etc.), would have to be quantified at a level considerably beyond the level of sensitivity desired for an actual target species, since the actual wavelength-dependent variation of the "signal" absorption would be mixed together with naturally occurring variations. Even if a "complete" catalog of environmental backgrounds existed, the problem of a lack of knowledge of the actual background (as opposed to the model background) would still be present. The problem is operationally significant because information about potential CW species is almost always desired for a remote site for which *a priori* knowledge is limited. The group at Aberdeen in particular is to be commended for their measurement program, which strikes to the core of this background uncertainty problem.

A realistic (but currently unmet objective) would be the achievement of reliable signal detection corresponding to absorption coefficients $\gamma = 0.01$ (that is, to 1% changes in power due to the target species). Unfortunately, the estimates of column densities given above (which depend linearly on the assumed rate of emission of about 1–2 kg/day) typically lead to absorption coefficients 10 to 100 times smaller than this detection limit (even for unscrubbed emissions), except in the most optimistic situation. We therefore conclude that remote sensing by LIDAR from either a satellite or an aircraft at ranges of 100 km is not apparently a viable strategy for the detection of CW production. Since this conclusion rests on an analysis of the detection of the toxic agent itself (e.g., GB), one might argue that detection of intermediate chemicals in the production process would offer better prospects, since their concentrations in the stack emissions can be much higher. Such a process would, of course, require a detailed comparison of the various patterns of emissions signatures for a proliferator relative to a legitimate industrial operation, but might be profitable to explore in more depth.

We should perhaps note in passing that LIDAR has been employed within the context of environmental monitoring of airborne chemical effluents, and has achieved sensitivity below the ppm level (for species of comparable absorption cross-sections to those relevant for the detection of CW production). [26] However, it should be emphasized that the situation for environmental monitoring differs markedly from the task of remote detection of CW production, in environmental monitoring measurements are usually made from a stationary vehicle over a long observation time, enabling a more complete characterization of backscatter and backgrounds. This is in sharp contrast to remote sensing of a largely unknown site from a satellite or from a distant aircraft.

7.5.2 LIDAR for Agent-Specific Warning of CW/BW Use on the Battlefield

Various other scenarios in addition to the detection of the CW production facility discussed above can be evaluated for analysis by LIDAR, including warning systems for CW/BW attacks on the battlefield. [21] A summary of Batelle's findings can now be assessed within the context of the analysis performed above.

Assuming a minimum detectable absorption coefficient $\gamma = 0.01$ (corresponding to a fractional change in power of 1% due to the "signal" species) and a "typical" absorption cross section of 10^{-3} m^2/mg as in Batelle's Figure 7-1 (corresponding to $\sigma = 2 \times 10^{-18}$ cm^2), then the minimum detectable column density $CL_{\text{min}} = 10$ m^2/mg. Note that this value is associated with detecting a change with signal-to-noise ratio of order unity and not to the much more challenging task of actual identification of the chemicals giving rise to the signal change. Nonetheless, taking $CL_{\text{min}} = 10\ \text{m}^2/\text{mg}$, we now comment in more detail on the different scenarios of concern.

The values of CL resulting from a blast are large and could give rise to detection of agent use with high signal-to-noise ratio. Unfortunately, this condition persists only over a relatively brief transient whose duration depends upon the actual details of the release (including the local weather) and on the vapor pressure of the particular agent. Durations of detectable signals might be of order hours to days. However, high values of CL are obtained for a time following the initial blast of only 15 seconds, which is a time where one might reasonably expect a considerable amount of dust and debris in the air to obscure the desired signal species. [21] Nonetheless, a properly programmed system might first characterize backgrounds at the relevant site and hence be in a position for sensible monitoring of the transient in some "window of opportunity" after the debris has settled out but before the signal species has decayed away. Given the expected large releases of material following the blast, an alternate strategy might be the physical collection of samples by a down-wind system. Cueing the system to some of the probably large number of artillery attacks is seen to be essential in identifying whether CW/BW attacks have been performed in the presence of a large number of conventional munitions or not.

The Batelle study also evaluates the concentrations of agent released after CW attacks on ground troops either by shelling or by missiles. Relative to the proposed value for the minimum detectable column density $CL_{\text{min}} = 10\ \text{m}^2/\text{mg}$, the concentrations expected were reasonably high. These situations are therefore potentially amenable to LIDAR warning systems, provided that the system can be cued and that issues related to background characterization, dust, clutter, etc. can be addressed. Also, immediately following the attack, the concentrations of toxic agents will likely be inhomogeneous across the battlefield. Note that the values of column densities given in this computation were, however, computed for a time of 30 minutes after the attack, which as a practical matter is the time required to obtain a reasonably homogeneous distribution for meaningfully defining a global column density, but which is an unreasonably long time relative to the onset of lethality for the CW. Presumably, local sensors distributed among the troops themselves could provide (or replace) LIDAR identification of threat in this case. Stated more succinctly, if the release is by a blast directly overhead, then the threat is apparent.

7.5.3 LIDAR for Battlefield Detection of Suspect CW and BW Clouds

The JASON study group also received information related to the possible LIDAR-based detection of BW use, for example either on the battlefield or at supply staging areas. [22, 24, 25] Since the signatures are too low in concentration to detect, our general recommendation is to concentrate on prompt alerts and tracking of potential threats, with actual identification provided by an array of other cued sensors (for example, the micro-UAVs discussed in Section 3). In this context, a viable, useful role of a LIDAR system might be to recognize clouds of specific morphology (without actually identifying the cloud composition), as might be expected from the release of aerosols containing BW. We note in particular the progress of the LANL group, that has tested a Nd:YAG LIDAR system for the detection of simulants of biological agents. [22] The system is based upon elastic backscatter of the incident radiation and hence provides no specific identification of the composition of the threat cloud. However, it is field portable and was tested in a Black Hawk helicopter, resulting in a rapid coverage of large areas. On the whole, we strongly endorse such a detection philosophy.

A system that does offer the potential for identification by remote laser ranging is based on detection of UV fluorescence (of tryptophan) following excitation by an excimer or other UV source. Given the low lethal concentration of biological agents, it is easy to see that detection by direct absorption is not feasible. For example, if we require a minimum absorption of 1%, and if we take the absorption cross section to be the geometrical area of the biological particle (that is, the particles are optically thick [24], then the minimum detectable concentration by an absorption measurement would be 5×10^5/litre for 0.8 μm particles distributed over a 40 m path, which is far above the lethal level of roughly 10^2 spores/litre as appropriate to anthrax, for example. On the other hand, the number of fluorescent photons returned might be more readily detected. As a reference point, consider a system composed of a 1 J pulse at 300 nm with a collection aperture of 1 m, with input and output efficiencies of 50%, and with other conditions as above, corresponding to a particulate density of 5×10^7/litre (for 0.8 μm particles distributed over a 40 m path). Hence the "canonical" lethal dose of 10^2/litre represents only 20 detected photons for the parameters of our example. Of course presumably any real threat cloud would initially have concentrations considerably in excess of the actual lethal dose level.

The best calibration of possibilities for detection by UV fluorescence that we have seen is the work of Wilson and Karl, [22, 25] with a very useful data base having been assembled by Bischel [24]. While the results of this work are most encouraging, one of our principal concerns centers on the need to quantify various naturally occurring backgrounds (e.g., pollens), as well as possible man-made and battlefield interferences. We are not at all convinced that anthrax spores, for instance, will be detectable in the presence of naturally occuring backgrounds of pollen grains, mold spores, fluorescent aerosols, etc. The pollen loads in air vary drastically from hour to hour, from day to day, and from week to week, depending on the blooming seasons of plants and the weather. [27] Quantitative data are sparse, but some references indicate that the normal loading of pollen and mold spores in the air ranges from 1 to 100 grains per liter. [24, 27]

Since pollen and mold spores are typically tens of microns in diameter while bacterial spores are on the order of a micron or less, the fluorescent return from a pollen or mold spore could be 100 to 1000 times larger than that from a bacterial spore, depending on whether the fluorescent signal is proportional to the surface area or the volume of the spore, and the relative concentrations of fluorescent materials in the spores. Thus, the fluorescent return from 1 to 100 pollen or mold spores per liter of air could be the same as the fluorescent return from 100 to 100,000 anthrax spores per liter of air. This could be a serious problem since 100 anthrax spores per liter of air would be lethal to an unprotected human, yet such a concentration might not show up in the fluorescing background.

A further concern beyond the levels and fluctuations of naturally occurring backgrounds is the possibility of false signatures associated with the battlefield (e.g., dust and residues from detonations). Note that some common anthropogenic pollutants such as partially burned jet fuel fluoresce efficiently, perhaps because of aromatic contaminants. Finally, some consideration must be given to possible encapsulation of the biological agent. This is frequently done with bioinsecticides like BT spores to provide protection against damage by ultraviolet light from the sun, so the technology is in hand to encapsulate human pathogens as well. The same encapsulating material could also be used to suppress fluorescence, thereby defeating this detection method entirely.

Apart from techniques based upon laser ranging considered in this section, other areas for investigation also seem promising. For example, if one seeks to detect a "biological" cloud of dimensions of 1 km $\times$ 100 m $\times$ 100m, then passive IR imaging should be considered. Better still is to focus on the delivery vehicles themselves; dispersal of viable biological agents over large areas is nontrivial and as discussed above, the proverbial "crop duster" should be readily identifiable and targeted for attack.

8 PASSIVE DEFENSE ACTIONS AFTER BW/CW ATTACK

We were informed during a briefing from the Army of the current training and procedures for passive defense after a CW/BW attack. Of course, personnel don protective gear after an alert, but tanks and planes must be decontaminated as well. Most of these measures are generally low-tech and are moderately effective at present. However, many small improvements could possibly be made in order to streamline the operation and to make dealing with the effects of an attack more efficient overall. Some suggestions are described below, along with potential technologies that may be applied to the relevant problems.

8.1 Decontamination of Planes and Tanks

We were informed that decontamination of tanks and airplanes from a BW/CW attack is currently performed by pouring 55 gal drums of a decontamination solution onto the exterior surfaces of the affected equipment. The liquid is so caustic that in decontaminating the equipment it causes corrosion of the metal. In addition, the liquid is difficult to handle by the military personnel and would create a clean-up problem if it were required to be used on a large scale. The use of such large quantities of liquid also presents a logistics problem to insure that sufficient quantities of the solutions are available everywhere on the battlefield in the event of a CW/BW attack.

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There are several possible alternatives to merely flushing the exterior surfaces of the equipment with a caustic solution. The solution can decontaminate large quantities of BW/CW agents, and so to be efficiently utilized should be recovered and recycled. A mobile "tank wash" tent, not unlike a car wash station, could be developed for this purpose. A flexible tent lined with teflon or other resistant material would be erected and the tank driven inside the tent. The tank would be exposed to the caustic liquid, which would be collected and then pumped into a reservoir for reuse. If desired, a second rinsing station could also be prepared in which the tank would be exposed to water thereby minimizing the exposure time of the metal to the caustic solution. Such a tent structure could be very light and could be easily transported in a folded state and readily erected where needed. It could even contain a sensor suite to detect when the rinsing water was contaminated with unacceptable levels of residual BW/CW agent so that the caustic solution should be replaced.

In principle a similar approach could even be used to decontaminate aircraft, except that here one probably wants to drape a flexible tent over the fuselage and wings of the plane and then collect the corrosive rinsings for recycling. Sensors in the water drain stream could be used to specify when a new solution is needed, and many spray points along the fuselage and wings could be readily obtained through perforated teflon-coated tubing, for example that is used to provide the structural form for the tent.

A third possibility is to use ozone or ethylene oxide to decontaminate military equipment, much as these gases are used to decontaminate equipment used for household gardening after application of BT for pest control. Ozone seems more attractive for this purpose because it could be generated electrically in situ from air; the gases have the advantage that they will penetrate into the interior areas of the vehicle (where personnel are likely to contact BW/CW agents) as opposed merely to decontaminating the exterior surfaces of the tank or plane. Again it seems possible to construct a lightweight chamber that could be continuously purged to maintain a positive pressure of gas; the tent would confine most of the gas and recycle it, and the vehicles/planes would enter the tent for decontamination purposes and then leave when the process was completed.

8.2 Non-Stick Coatings for Tanks

A related issue brought to the attention of the JASON study group is that the surfaces of tanks and planes are difficult to decontaminate because they are porous and the BW/CW agents creep into the pores, making the agents difficult to access with the liquid decontamination solutions. The gaseous decontaminants should alleviate this difficulty. In addition, a newly developed coating, which is teflon-like but which is non-porous, and to which nothing that was tested actually adhered, [7] might be applied as a colorless, thin coating over the paint of existing vehicles in order to reduce the surface porosity and facilitate their decontamination by existing procedures.

8.3 Weather Prediction

After an attack, a keep-out zone, in which personnel are not supposed to operate without protective gear, is designated according to protocols in the Army field manual. These zones are based almost exclusively on the prevailing wind direction and speed, and on some very conservative (and old) estimates of the likely dosage of a CW or BW attack. Since performing military operations in full protective CW/BW gear is cumbersome and leads to inefficiencies, it would be highly desirable to obtain more accurate, situation specific estimates of the spread of a BW/CW cloud after an attack.

There are two approaches to this problem. The first is to utilize pre-existing models of the terrain and general trends in the local meteorology around the theater of interest in conjunction with cloud dispersion models. In this fashion, some generic estimates could be obtained for the dimensions of keep-out zones under a range of meteorological conditions that might be typically encountered in the area of potential attack. General descriptions of the existing wind and weather conditions at the time of a confirmed attack would then be sufficient to refer to the correct keep-out zone estimate.

A more refined approach would be to use more extensive meteorological inputs, and to routinely collect such data in a battlefield environment in times of conflict. Wind speed, wind direction, temperature, pressure, and relative humidity instrumentation is very portable and could be mounted on certain tanks or in field stations to obtain a real-time data set for the theater of interest. In this fashion, the data could be input after an attack into a simulation model so that the cloud movement might be estimated and a better keep-out zone estimate performed.

We are, however, skeptical of an ability by any such models to predict precisely the path of an individual cloud under any reasonable set of real-world conditions. These efforts should be viewed as a method of improving upon the "worst-possible case estimate" scenarios currently in the field manual, while still offering a conservative level of safety and not unduly inhibiting normal military operations.

8.4 Vaccines

Although vaccination is a prudent procedure for troops going into harm's way, it should be pointed out that without excellent intelligence information on the nature of the BW stockpiles of an opponent, there are so many potential viral, bacterial, and biotoxin materials which could be used as powerful BW agents that vaccination of one's troops would only be truly effective if all such agents that have been produced and weaponized by the enemy could be anticipated well in advance. Otherwise, vaccination against a particular strain of anthrax, for example, may not prove to be effective against another type of anthrax strain. The problem will become even more difficult as biotechnology advances, and as mutant strains of a large number of possible BW agents can be readily prepared and inventoried for BW production with relatively little expense and effort. Also, given the amount of time needed to grow antibodies, to obtain a vaccine, and then to vaccinate all of one's troops, relative to the 1–2 weeks necessary to produce a militarily significant quantity of a new BW strain through fermentation of a mutation, it is very reasonable to envision that an adversary could find out which strains its opponent's troops have been vaccinated against and then simply prepare a BW with another strain for use as an effective weapon. Such an approach of course assumes a very desperate adversary who will possibly risk exposure of his own, unvaccinated, personnel to the effects of the attack. (Otherwise, we only vaccinate our troops when the opponent vaccinates his, and use the same type of vaccine as he is using, or we use a superior one.) In this scenario of desperation, however, the only information one might actually obtain about the specific strain in the BW agent, prior to its use, may be available through humint. In the absence of humint, vaccination may make some troops feel better about being deployed to the battlefield, and in this respect may be useful and needed in practice.

9 OVERALL ASSESSMENT OF U.S. DEFENSE COUNTERPROLIFERATION PROGRAM

A successful DCI program will require many players, including DARPA, DSWA, the military services, etc. In an initiative such as this, it is natural for each participant to try to shoehorn preexisting programs into the new initiative. We urge the DCI management to resist this tendency by defining important and realistic program goals that are not subordinate to preexisting institutional capabilities.

Secondly, we note that enthusiasm for programs waxes and wanes very quickly in Washington. To provide some continuity to the DCI, we strongly recommend that a high-level oversight committee be formed to provide long term stability and a corporate memory. Such a committee would report to an appropriate, high-level, official in DOD. We have in mind a group analogous to the President's Foreign Intelligence Advisory Board, which has been successful in sustaining broad support of sensible intelligence efforts from administration to administration. The committee should have a majority of experts who do not represent potential "contractors" for the DCI. We recommend that the committee include members from communities which have not traditionally participated in counterproliferation technology programs. For example, the greatest hands-on experience with technologies related to chemical and biological warfare resides in the civilian insect and pest control business. Humans share large numbers of enzymes with rodents and even insects, so the insights acquired from insect and pest control would have many applications to the problems of biological and chemical warfare. One or more individuals with extensive knowledge of agricultural insecticides, their production and application, should be on the oversight committee. Other

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valuable members of the committee could come from the Center for Disease Control, from the civilian remote sensing community at NASA, from the meteorology community, etc.

The DCI, as briefed to the JASON study group, followed the priorities of the Deutch report [1] quite closely. The DCI is placing a heavy emphasis on the three highest priorities identified by the Deutch report: (1) warning of chemical and biological warfare attacks; (2) defense against chemical and biological warfare on the battlefield; and (3) detection, characterization, and defeat of underground structures. While the priorities of the first two items are self-evident, we have difficulty understanding the heavy emphasis being placed on item (3), especially as regards hard vs. functional kill. We suggest that the potential return on investment to the overall program is not as high for item (3) as it is for items (1) and (2).

We do not wish to underestimate the importance of humint. Once a commitment has been made to incorporate chemical or biological warfare into regular military forces, the opportunities for both humint and technical intelligence increase greatly, since many more people will be involved, many training exercises will take place, etc. Since humint is so important, we strongly recommend that the DCI provide guidance to the intelligence community on what to look for in constructing instruments for on-site sampling of suspect sites and also that the DCI work closely with the intelligence community to identify key telltales of a proliferation program that could be emphasized during the course of humint collection.

With respect to battlefield detection of CW/BW use, we recommend the development of layered strategies involving diverse detection schemes. At long range, generic signatures of potential threats should be sought, for example detection of aerosol clouds, aircraft which seem to be crop dusters, unusual artillery rounds, etc. With such cues, more specific identification could be undertaken. Increased emphasis should be placed on schemes that bring the detector close to the suspect source, either by using small UAVs to obtain samples and return them to a mobile laboratory for analysis or by launching a small inexpensive sensor package into the suspect region in order to corrobate an initial generic alarm. In the field, capabilities for local threat assessment should be broadly distributed to small units of soldiers, and initial warning alarms should be constructed to be generic in nature as opposed to agent-specific. We specifically advise against a program centered around a few complex (and expensive) systems of limited case-specific utility and mobility. Instead, the program should strive to develop capabilities with sufficient agility to adapt easily to a modified spectrum of threats and to a rapidly changing battlefield environment.

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Adelphi,MD 20783-1145

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ZETA Associates
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1801 North Beauregard Street
Alexandria, VA 22311

Dr Ari Patrinos [5]
Associate Director for
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US Department of Energy
1901 Germantown Road
Germantown,MD 207874-1290

Dr Bruce Pierce
USD(A)D S
The Pentagon, Room 3D136
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Chief Science Advisor
USACDA
320 21st Street NW
Washington, DC 20451

Dr George W Ullrich [3]
Deputy Director
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22310

Dr. David Whelan
Director
DARPA/TTO
3701 North Fairfax Drive
Arlington, VA 22203-1714

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Dep Assistant Secretary of the Navy
C3I Electronic Warfare & Space
Department of the Navy
The Pentagon 4D745
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