The Search for Unexploded Ordnance

J.R. Deschamps
Laboratory for Structure of Matter

A.W. Kusterbeck
Center for Bio/Molecular Science and Engineering

Introduction: The Navy and other military organizations have instituted programs to remediate Formerly Used Defense Sites (FUDS). Often this means removing unexploded ordnance (UXO) from a site that was used for training, or was contaminated due to the sinking of a ship, or the unintentional destruction of storage or manufacturing facilities. Navy sites may be partially or completely under water. At any of these sites, UXOs need to be located and either removed or rendered harmless.

With current technologies, UXOs are located based on imaging (such as sonar) or metal content (magnetometers). These methods are very good at finding objects, but they cannot distinguish between UXOs and harmless debris. An explosive ordnance disposal technician makes this distinction by manually investigating each target. This process is dangerous, time-consuming, and expensive. Cleanup and site remediation would be greatly facilitated if an accurate means could be developed to identify those objects that contain explosives.

A major goal of the Chemical Sensing in the Marine Environment program (CSME) has been the development of novel means to detect and locate UXOs in marine environments. Research involves detection of very low concentrations of explosive residue, sampling strategies for data collection, and data analysis to locate the source of the explosive residue. Technologies developed in this program have several uses. Monitoring environmental remediation of explosive contaminants may be used to support the Navy's Mobile Underwater Debris Survey System and may be applied to monitoring manufacturing process streams.

CSME Strategy: A primary obstacle in developing strategies for UXO location in the marine environment is that no currently available chemical technique is capable of directly detecting trace explosive residues in seawater. Early efforts to measure low concentrations (i.e., high parts-per-billion (ppb) range) of explosives in seawater suffered from problems with sample handling and stability. Passivating the sample bottles and adding a preservative eventually solved these problems. This was not the final solution. A more realistic estimate for concentration of explosives leaching from a UXO is in the low ppb to high parts-per-trillion (ppt) range. As a result of a multidisciplinary effort involving NRL, other government laboratories, and several universities and private businesses, an effective technique for concentrating explosive residue contained in 100 liters of seawater by 5000-fold was developed. This method allowed measurement of the trace concentrations of explosives expected from UXOs. Various sources of explosive residue were then characterized to determine the actual concentration of explosives leaching from these targets in seawater, and the time course of the leaching. Based on these experiments, it was concluded that explosive residues leaching from UXOs could be used to locate UXOs.

Later work examined the characteristics of the plume resulting from chemicals released in the water. A typical plume was previously thought to have a Gaussian cross-section (Fig. 1, (A)). Although a Gaussian shape is a fair representation of the average behavior of a plume, the actual cross section is more complex (Fig. 1, (B) and (C)). There is some evidence that the extra information contained in these real cross sections is used by organisms trying to locate food or a mate. Thus, sensors with a rapid response time may allow this extra information to be used in locating UXOs based on their chemical plume.

The NRL Flow Biosensor: The Naval Research Laboratory has worked for many years to develop biosensors capable of detecting explosives. By using antibodies in a displacement assay to recognize an explosive and fluorescence to signal recognition, a fieldable sensor for detecting low concentrations of explosives in groundwater was developed. The first-generation biosensor (Fig. 2) was used in field trials to monitor groundwater contamination at military installations.[1,2] As with other chemical sensors, this sensor could not measure trace levels of explosive residue in seawater. Therefore, a program to improve the sensing element was initiated. Using the CSME data as a guide, improvements in the assay protocol and sensor format were made. These resulted in the ability to directly detect low concentrations of explosive residue in 90% seawater. In support of the CSME program, a second-generation biosensor is being miniaturized for deployment in the ocean. The prototype biosensor will be a stand-alone instrument that measures up to six chemicals simultaneously in seconds and can be operated at depths up to 100 meters.

Deployment of a Chemical Sensor: A number of methods can be used to deploy chemical sensors for locating the source of a chemical plume in the marine environment. These typically consist of

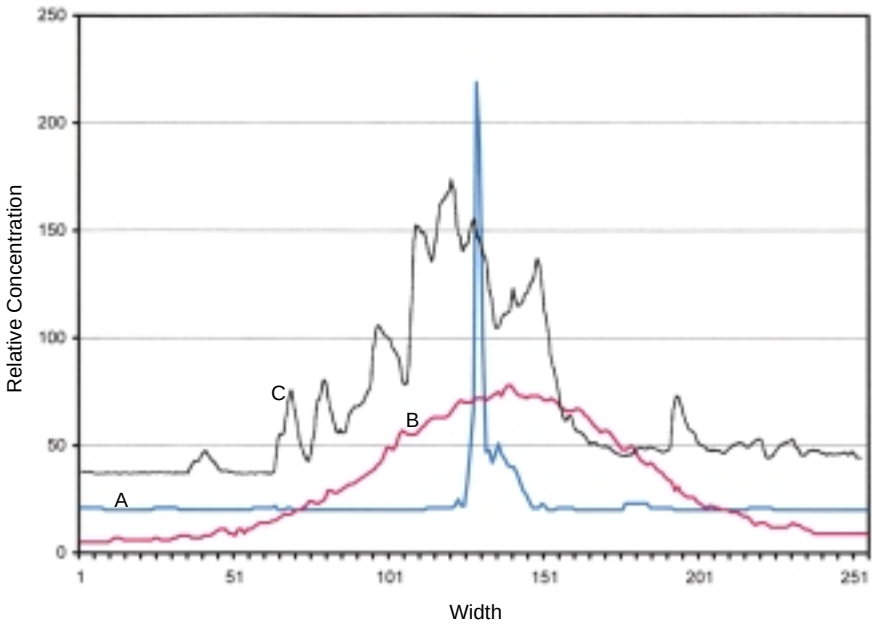

FIGURE 1
Plume cross-sections (off-set vertically for clarity): blue - time averaged showing typical Gaussian profile (A); magenta - instantaneous cross-section, part of series averaged to produce profile A (B); black - marine plume recorded during ONR-sponsored field test (C). [Cross section generated from data supplied by J. Crimaldi, M. Wiley, and J. Koseff (Stanford University).]

FIGURE 2
Setup for field operation of current-generation NRL flow biosensor. To assay for explosives and measure concentrations, samples are injected into the instrument and moved by a fluid stream to immobilized antibodies. Any increase in fluorescence is observed within minutes and stored on the computer for later data analysis.

FIGURE 3
AUV (REMUS) used in plume-mapping experiments. Sensing elements are contained in the white nose cone, a current profiler is in the green section, and vehicle controls and batteries are in the central yellow section. The inset shows the AUV while deployed in a plume mapping experiment. [Images courtesy of SPAWAR.]

towed systems or diver-deployed systems. A recent development in experiments aimed at mapping and tracking plumes has been the use of autonomous underwater vehicles (AUVs) for data collection (Fig. 3). Using an AUV, all data required for locating the source of a chemical plume can be rapidly collected from a single platform. The miniaturized flow biosensor can be deployed on such a platform.

Future Plans: Through continued improvements in the sensing element, it is expected that the biosensor will have sufficient sensitivity to directly detect plumes from UXOs in the marine environment. Over the next one to two years, NRL will be field testing the next-generation biosensor and working to integrate the sensor into an AUV. This combination will provide the desired novel means of detecting UXOs and will remove the Navy diver from the location and identification phases in any cleanup effort.

Acknowledgments: Research described in this report was supported by the Office of Naval Research

and represents the results of a collaboration among NRL, NSWC-CSS, SPAWAR, NAVEODTECH, ORNL, CRREL, Sandia, Areté Associates, Thorleaf Research, Stanford University of California at Berkley, and Rutgers University.

[Sponsored by ONR]

References

[1] P.T. Charles, P.R. Gauger, C.H. Patterson, Jr., and A.W. Kusterbeck, "On-Site Immunoanalysis of Nitrate and Nitroaromatic Compounds in Groundwater," *Envir. Sci. Tech.* **34**(21), 4641-4650 (2000).

[2] U. Narang, P.R. Gauger, A.W. Kusterbeck, and F.S. Ligler, "Multianalyte Detection Using a Capillary-based Flow Immunosensor," *Anal. Biochem.* **255**, 13-19 (1998).

Low-Cost, High-Sensitivity Atmospheric Ozone Detector

C.M. Roland and P.H. Mott
Chemistry Division

Introduction: Ozone, the triatomic allotrope of oxygen, occurs naturally from exposure of atmospheric oxygen to ultraviolet sunlight or electric discharge. Indeed, the characteristic fresh odor following thunderstorms is due to the ozone produced by lightning. Among common oxidants, ozone has the highest oxidation potential (2.1 V), leading to various commercial uses. These include as a disinfectant in the medical and food industries, for drinking and wastewater treatment, to suppress mold in storage facilities, and as a bleach. An increasingly popular application of ozone is as a deodorant. Hotels, for example, use ozone to purge tobacco odors, where it functions by oxidizing the phenol byproducts in the smoke. As a measure of its deodorizing effectiveness, one gram of ozone is reputed to neutralize the odor from a liter of hog manure.

There is a downside to the high reactivity of ozone. It is a strong respiratory irritant and is even toxic at high concentrations. The smog cycle, common to urban areas, is initiated by the photodissociation of atmospheric oxygen to produce ozone in the presence of hydrocarbons. The American Lung Association considers ozone to be the greatest airborne public health threat in the Washington, D.C. area. During the summer of 1994, for example, 600 hospital admissions in the region were attributed to high ozone levels. Metropolitan areas throughout the United States habitually fail to comply with the Environmental Protection Agency's air quality standard of 120 ppb average ozone level.

The environmental hazards of ozone, along with industry's increasing use of it, have led to the demand for a sensitive, inexpensive method of ozone detection. Existing analytical instruments are expensive and ill-suited for field use, while portable methods (e.g., the Draeger tube) suffer from poor accuracy and interference by other chemicals. Recently, work at NRL has shown that ambient ozone levels can be quantified by measuring the opacity that accompanies ozone-cracking of rubber films. This has been developed into a technique for detecting atmospheric ozone that is portable, inexpensive (few dollars), and combines high sensitivity (1 ppb atmospheric ozone, 100 times less than the OSHA safety limit) with a broad dynamic range (at least six decades).[1]

Background: When an unsaturated hydrocarbon elastomer is exposed to ozone, rapid reaction occurs to form an unstable ozonide ring (Fig. 4). This structure rapidly dissociates, severing the polymer backbone. If the rubber is stretched during this process, a surface crack is produced. As these cracks accumulate, light scattering from the rubber surface gives rise to a translucent ("frosted") appearance. The rate at which the surface cracks grow is governed by the availability of ozone; thus, the loss of optical transparency can be directly related to the ambient ozone concentration.[2]

Results: The sensing material is an initially transparent, elastomeric film (e.g., 1,4-polybutadiene crosslinked with dicumyl peroxide). The degree of crosslinking and the applied strain determine the mechanical stress, and hence the ozone-sensitivity of the rubber. A minimum level of stress (ca. 0.2 MPa) is necessary for crack initiation; ozone-induced hazing will not occur if the rubber is unstretched.

The spacing of cracks on the rubber's surface is determined by the number of nucleation sites, which in turn depends on the applied stress. To produce a

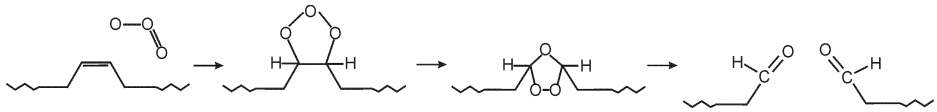

FIGURE 4
Ozonolysis of stretched rubber involves formation of a molozonide structure, then an ozonide ring. The latter rapidly decomposes, propagating a surface crack.

uniformly frosted appearance, crack initiation must be profuse, requiring somewhat greater stress than the minimum necessary for any cracks to initiate. This is illustrated in Fig. 5. If the stress is too small, only large, isolated cracks appear, while higher stresses produce a plethora of mutually interfering cracks, roughly 10 mm in size.

The ozone level associated with loss of transparency in the material is also governed by the stress. Using a tapered geometry to vary the strain, a range of sensitivities can be obtained from a single test specimen (Fig. 6). The narrower section of the sample, where the stresses are higher, becomes opaque before the wider parts. The result is a "frosting front" that propagates from along the sample. The same effect can be accomplished by changing the crosslink density within the sample.

Two modes of operation are envisioned for this technology:[3] a simple, disposable "litmus paper" type detector, and a more elaborate device, using, for example, a spool that dispenses the rubber for stretching and measurement, in combination with a take-up spool that unstretches it for archival storage.

Figure 7 shows relative transmission as a function of exposure time for five ozone concentrations. The conversion of the measured opacity to ozone concentration is done by means of a calibration curve. The rubber's response to different conditions, such as strain or exposure time, can be superimposed to yield a "master curve." This facilitates implementa-

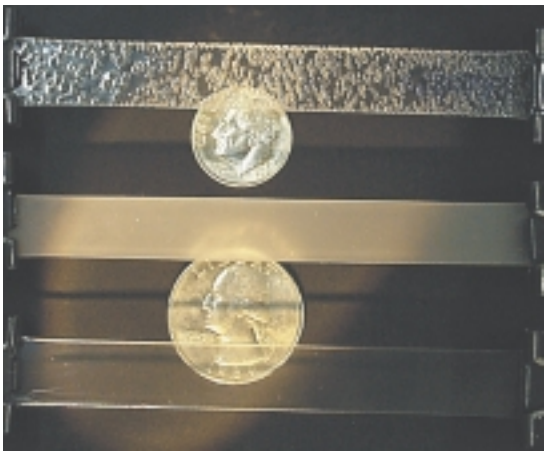

FIGURE 5
Polybutadiene exposed to 10 ppb ozone for 24 hours. The lower strip is unstrained, and remains identical in appearance to unexposed rubber. The middle strip, stretched 121%, is almost opaque, due to a uniform coverage of surface cracks, 5-10 mm in depth and spaced about 20 mm apart. The strip at the top had a strain of 18%. The resulting stress was only sufficient to induce distinct, well-separated cracks, corresponding to the largest inherent flaws.

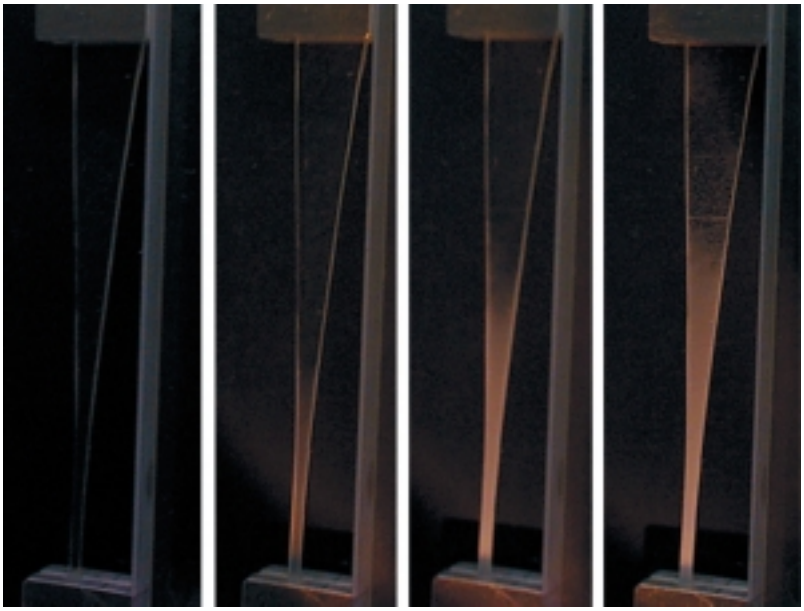

FIGURE 6
Stretched polybutadiene exposed for 0, 4, 8, and 120 minutes to 200 ppb ozone. The cross-sectional area varies by a factor of four along the specimen length. The consequent variation in stress causes the observed varying response to ozone.

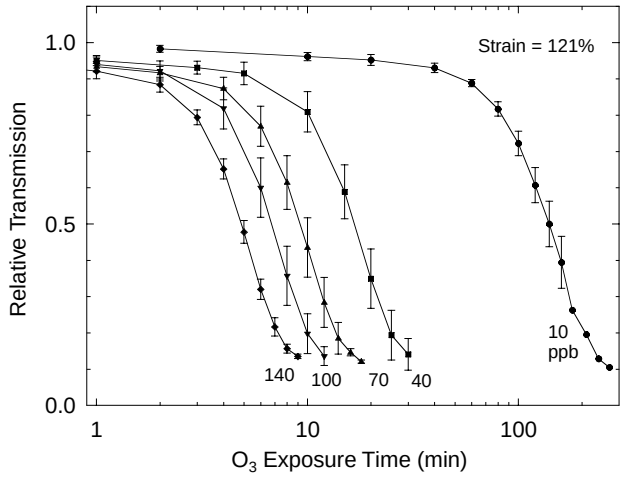

FIGURE 7
Change in optical transparency of polybutadiene stretched 121% while exposed to the indicated levels of ozone.

tion of the method, enhancing both the sensitivity and dynamic range.

Since ozone will not necessarily be the only air pollutant present, it is important to demonstrate that the test method is free from interference. We have determined that exposure to specific pollutants (sulfur dioxide, carbon monoxide, methane, nitrogen dioxide, nitrogen monoxide) has no influence on the response of the stretched elastomer to ozone. This is not surprising, since ozone is much more reactive than these gases.

Summary: Transparent rubber stretched in an ozone-laden environment initially develops micron-sized surface cracks due to ozone-induced chain scission. The consequent reduction in the transparency of the rubber provides a facile method for measuring ambient ozone levels. The loss of light transmission is linearly dependent on the ozone concentration, and is an increasing function of the strain. This method of detecting atmospheric ozone has high sensitivity (1 ppb) and a broad dynamic range. Environics, Inc. of Tolland, Connecticut, has obtained a license from the Navy to market the technology.[4]

Acknowledgments: We thank Environics, Inc. for the loan of their ozone generator and analyzer.

[Sponsored by ONR]

References

[1] C.M. Roland and P.H. Mott, "Atmospheric Ozone Concentration Detector," U.S. Patent #5,972,714, October 26, 1999.
[2] P.H. Mott and C.M. Roland, "Ozone Detection by Crack-Induced Opacity in Rubber," *Rubber Chem. Tech.* **72**, 769 -778 (2000).
[3] P.H. Mott and C.M. Roland, "Disposable Elastomeric Ozone Detector," *NASA Tech. Briefs* (September 1997).
[4] "Partially Exclusive License Between Environics, Inc. and the United States of America," NRL-LIC-98-2-039, October 19, 1998.

The BARC Biosensor

L.J. Whitman,[1] P.E. Sheehan,[1] R.J. Colton[1], M.M. Miller,[2] R.L. Edelstein,[3] and C.R. Tamanaha[3]
[1]*Chemistry Division*
[2]*Materials Science and Technology Division*
[3]*Geo-Centers, Inc.*

Recent events in Yemen have made disastrously clear that acts of terrorism are one of the greatest threats to our Armed Forces. One of the most insidious threats is exposure to biological warfare agents. Unfortunately, treatments for infection by likely pathogens are currently limited, and may require treatment before any symptoms appear—the case for anthrax, for example. The invention of highly sensitive sensors for early detection of biological warfare agents is crucial. The Bead ARray Counter (BARC) system is a revolutionary tabletop biosensor we are developing at NRL to help solve this urgent national problem.

Gene Chips: The BARC biosensor is based on a so-called "gene chip." The function of a gene chip is to simultaneously look for a large number of distinct segments of deoxyribonucleic acid (DNA), the unique genetic material of life. Identification is accomplished by taking advantage of the unusual structure of DNA: two complementary strands that recognize one another, even in a complex mixture. An array of DNA spots (the "probes") is deposited on a surface (the "chip"), with each spot containing *single* strands of one particular segment of interest. When matching segments are present in a sample, they combine (hybridize) with their complements on the chip. The resulting double-stranded DNA molecules are typically labeled with fluorescent molecules. Then

a bright light is focused on the chip, and a special optical system "reads" which spots fluoresce.

Although the first commercial gene chips are proving useful for medical research, they fall short for biological warfare defense. Because very little light is emitted by the labeled DNA, a large, powerful, and complex optical system is needed to read a chip. Furthermore, to achieve the desired sensitivity—the detection of a few thousand DNA molecules or less per milliliter in the original sample—fluorescence-based systems require extensive sample preparation that may take hours to complete.

The BARC Approach: In the BARC biosensor, the fluorescent labels are replaced by magnetic labels that can be detected *individually* using an array of magnetic field microsensors embedded in the chip (Fig. 8).[1,2] The magnetic labels are commercial beads, 1 to 2 microns in diameter, containing some magnetic material. The magnetic field sensors are wire-like structures on the chip, a few microns wide, made of a special metal alloy that displays giant magnetoresistance (GMR). When a magnetic bead is present above a sensor wire, the wire's resistance decreases by a small, but detectable, amount. The more beads present, the larger the change in resistance. Hence, the BARC approach eliminates the optical system required for fluorescence-based detection, replacing it with simpler, more sensitive, and less expensive microelectronics.

The biochemistry underlying the BARC biosensor is illustrated in Fig. 8. The chip containing the GMR sensors is coated with thin layers of silicon nitride (~1 µm) and gold (~50 nm) to protect the electronic circuitry from the saline solution containing the DNA. A custom-designed arraying system then deposits 0.3 mm-diameter spots of single-stranded probe DNA over the GMR sensors, with one end of each DNA molecule specially modified with a sulfur atom to bond to the gold surface. The DNA segments are from genes of pathogens likely to be used for biological warfare, such as *Botulinum*, *Francisella tularensis*, and *Yersinia pestis* (responsible for botulism, tularemia, and plague, respectively). The genetic information was provided by the Naval Medical Research Center.

After depositing the probes, the remaining surface is coated with polyethylene glycol, a polymer that inhibits the sticking of DNA or microbeads in the areas outside of the spots. The sample is then introduced and allowed to hybridize with the probes. At this point in our system development, the sample DNA must first be prepared so that it is single-stranded and tagged with biotin, a small ligand molecule that binds very selectively (and strongly) with a special receptor molecule, streptavidin. Magnetic microbeads precoated with streptavidin are then allowed to settle on the chip, bonding strongly with any biotin present and thereby labeling the captured sample DNA. The beads that are not bonded in this way are easily rinsed off, and the remaining beads are counted by the GMR sensors, indicating the identity and concentration of any pathogens present.

The Sensor System: The BARC assay is done in a small, glass flow cell mounted on the sensor chip (Fig. 9). The chip carrier board is housed in a disposable plastic cartridge that contains the reagents for the assay. The cartridge plugs into the electrical control system and interfaces with a miniature pump (not shown) that regulates the fluid flow. The overall system is operated with a laptop computer. A demonstration of the BARC biosensor is illustrated in Fig. 10. The eight sensor regions on the chip were each coated with gold. Two of each were arrayed with four different probes (one a positive control), and an assay

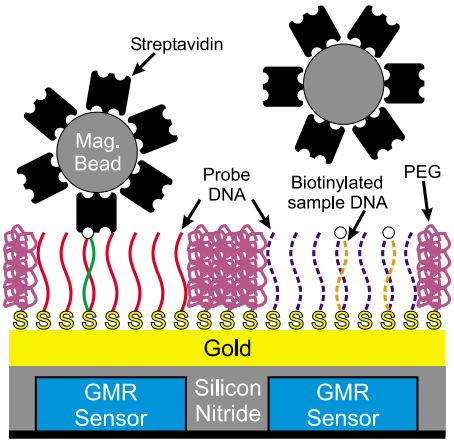

FIGURE 8
The BARC biosensor approach. Note that the elements are not to scale; in particular, the beads and sensors are much larger in proportion to the molecular components.

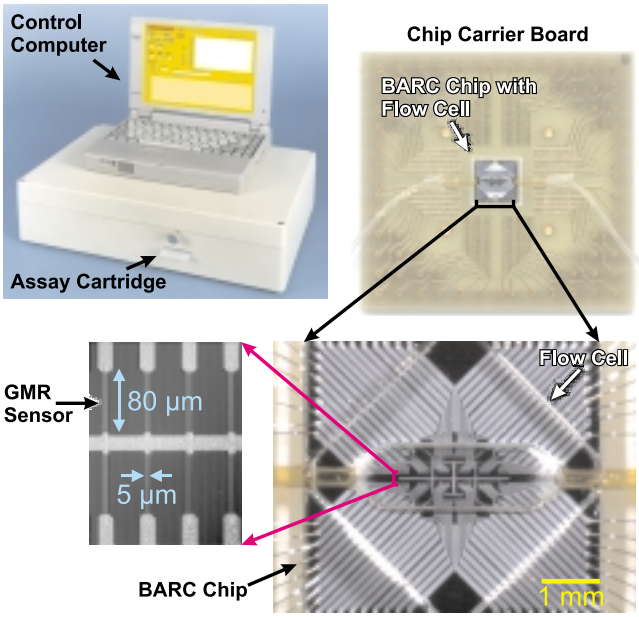

FIGURE 9
The BARC system and some of the internal components. The 5-mm-wide BARC chip (with the flow cell on top) is mounted on the chip carrier board, which is housed within the assay cartridge. The prototype chip shown has 64 GMR sensor strips, 5 × 80 µm each, in groups of eight.

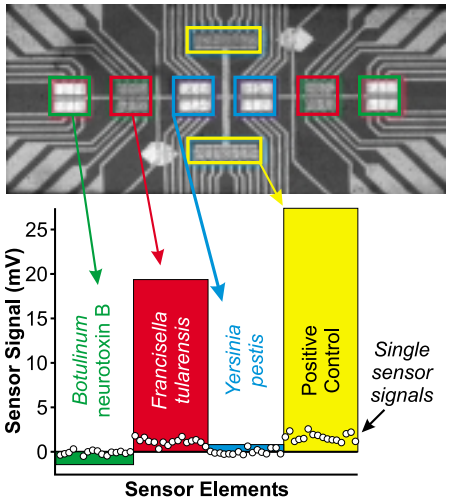

FIGURE 10
The results of a three-analyte assay. A view of the chip surface after the assay is shown, with the eight sensing regions outlined. The dark regions are almost completely covered with microbeads. For each analyte, the graph shows the measured signals from the individual sensing elements (symbols) and the integrated signal for all 16 elements (colored bar). The assay for *Francisella tularensis* was performed with 10 nM DNA hybridized for 30 min. The total assay required about 60 min.

was performed for *Francisella tularensis*. Afterward, the control and *tularensis* regions are densely covered with beads, while the other four sensor regions are nearly bead-free. The amount of DNA in the sample is measured by summing the signals from the sensors addressing each probe type (16 each).

Prospects for Further Development: The GMR sensor used in the BARC system is similar to technology being developed for a new type of computer memory, magnetic RAM. It should be possible to adapt this technology to make inexpensive BARC chips with millions of sensors. Ultimately, we hope to develop a small cartridge that can be plugged into a hand-held computer for rapid, sensitive detection of all known biological warfare agents. Such a system would also have broad commercial applications in the fields of biomedical research, diagnostics, drug discovery, forensics, agriculture, and environmental testing.

[Sponsored by DARPA and ONR]

References

[1] D.R. Baselt, "Biosensor Using Magnetically-detected Label," U.S. Patent 5,981,297, issued November 9, 1999.
[2] R.L. Edelstein, C.R. Tamanaha, P.E. Sheehan, M.M. Miller, D.R. Baselt, L.J. Whitman, and R.J. Colton, "The BARC Biosensor Applied to the Detection of Biological Warfare Agents," *Biosens. Bioelectron.* **14**, 805 (2000).

Better Use of Water for Fire Suppression

E.J.P. Zegers, P. Fuss, J.W. Fleming, B.A. Williams, A. Maranghides, and R.S. Sheinson
Chemistry Division

Introduction: Environmental concerns over the past decade have provided new impetus for expanding and improving the use of water for Navy fire protection. Traditionally, fire suppression in selected Navy shipboard compartments has been provided by Halon 1301 (CF_3Br), whose production has been banned in the United States and other developed countries because of its depletion of stratospheric ozone. Nonbrominated fluorocarbons, while ozone safe, are less effective, carry space and weight penalties for Navy platforms, are significant global warming agents, and produce toxic hydrogen fluoride (HF) gas in extinguishing a fire.

Water is perhaps the oldest firefighting agent, but it can be difficult to implement in many situations; because, unlike Halon, it is a liquid. Droplet size, transport, evaporation rate, and suspension time are all critical parameters in determining the effectiveness of a water-based suppression system against a given fire threat. Although water-based fire suppression has been the subject of empirical tests for many years, the interaction of liquid water droplets with flames has received surprisingly little systematic study in laboratory settings. The identification of the factors important in determining water's effectiveness as a fire extinguishing agent is a prerequisite for better implementation. The Navy Technology Center for Safety and Survivability has a coordinated program, combining fundamental laboratory studies of water/flame interactions with real-scale fire tests, to provide the Navy with implementation particulars for water mist-based fire protection systems.

Water Mist Fire Suppression: Traditionally, water has been used as a firefighting agent in the form of relatively large drops. Typical sprinkler systems produce water drops having diameters on the order of a millimeter. Such droplets are useful at cooling smoldering surfaces, but are relatively ineffective at suppressing combustion of gaseous or liquid fuels. The large size and low surface area/volume ratio means that relatively little of the water evaporates in the length of time the droplet spends near the fire. Thus the cooling provided by the water evaporation and dilution of the oxygen and fuel by the resulting water vapor are not efficiently achieved. For this reason, most water-based fire suppression systems use more water than would be needed if the thermal and dilution effects could be properly utilized.

Fine water mists, having diameters of 200 microns or less, circumvent these difficulties by allowing better droplet vaporization, but they are more difficult to produce. The tradeoffs between efficiency and engineering difficulties in droplet generation and delivery must be determined.

Laboratory Studies: In assessing the applicability of water mist fire suppression systems, one must answer the question "how effective can water be under ideal conditions?" We have investigated water mist inhibition and extinguishment in two types of laboratory flames and find that, under suitable conditions, water mist can be as effective as Halon 1301.

Figure 11 shows data taken in a nonpremixed propane/air counterflow flame, to which suppressants (Halon and water droplets of various sizes) were added to the air stream.[1] Addition of the suppressant to the air stream is the most typical scenario for most fire threats. The extinction strain rate plotted in Fig. 11 is a measure of flame stability. Effective fire suppressants lower the extinction strain rate as shown. Data for water and Halon, plotted on a mass basis, show that over the range of droplet sizes tested (20 to 50 microns), smaller droplets are more effective. Furthermore, water droplets of 14 and 30 micron diameter are considerably more effective than Halon, while droplets of 42-micron diameter are comparable to Halon in extinguishing this particular flame.

The degree of burning velocity reduction is also an indication the effectiveness of a fire suppressant. Figure 12 shows data on the burning velocity of premixed methane/air flames containing submicrometer diameter water droplets.[2,3] These droplets are small enough to completely evaporate during the short residence time (approximately one millisecond) in the flame region. In this type of flame, the effectiveness of the submicron water droplets is comparable to the findings for Halon 1301 in Refs. 2 and 3. Comparison of the water data to measurements with nitrogen and CF_4, two well-studied gaseous agents that are chemically inert and inhibit combustion by cooling and dilution of the available oxygen, indicates that the expected effect of water evaporation is achieved in this environment.

Achieving the maximum effectiveness of water in real fire scenarios is more challenging. The small drops that are most effective in the flame may evaporate before they reach the fire, while larger drops may be too large to be entrained in the air flow and get to the fire, especially for obstructed or cluttered areas. The key issues to understand are mist drop size and distribution in the protected space.

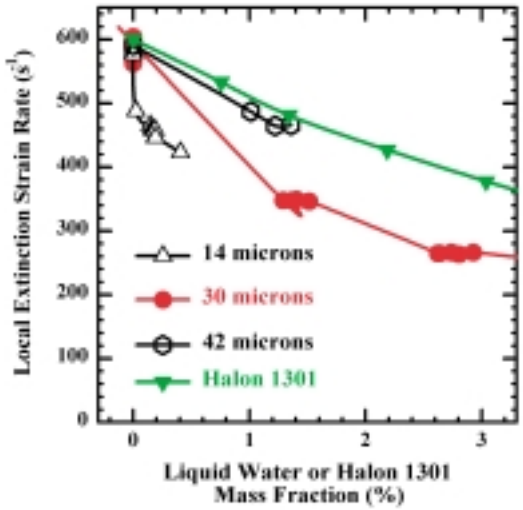

FIGURE 11
Measurements of extinction strain rate in nonpremixed propane/air flames inhibited by Halon 1301 (CF_3Br) and by monodisperse water droplets of various sizes (from Ref. 1).

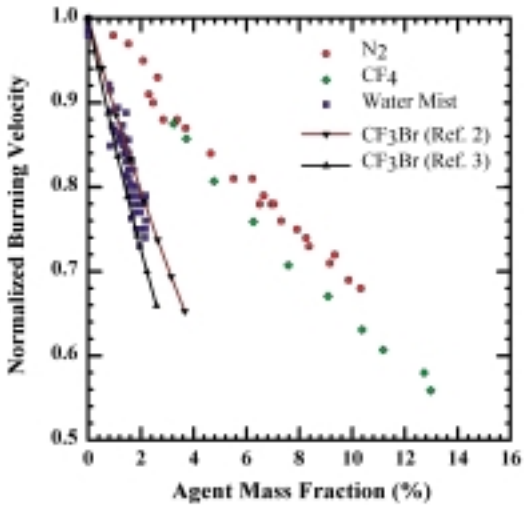

FIGURE 12
Measurements of burning velocity reduction in a methane/air mixture by addition of nitrogen, CF_4, and submicron water mist. Published measurements for Halon 1301 (CF_3Br) are also shown.

FIGURE 13
Fire test facility at the NRL Chesapeake Bay Detachment. The two enclosures at the rear (285 cubic meters) and the right (27 cubic meters) of the picture are used for testing different sized shipboard compartments.

Toward Implementation: Realistic large-scale tests are currently underway at NRL's Chesapeake Bay Detachment to develop water mist system implementation solutions to protect Navy shipboard flammable liquid storerooms against different fire threat scenarios (Fig. 13). These tests combine a powerful array of instruments to determine droplet sizes, velocities, and number densities at various locations in the test compartment, as well as the in situ measurement of oxygen dilution by the evaporating water mist, for truly understanding suppression by water mist. The detailed suppression mechanisms studies in laboratory flames combined with well instrumented full-scale studies is providing design guidance to the Navy for implementing water mist as an effective and reliable Halon alternative.

[Sponsored by SERDP and NAVSEA]

References

[1] E.J.P. Zegers, B.A. Williams, R.S. Sheinson, and J.W. Fleming, "Dynamics and Suppression Effectiveness of Monodisperse Water Droplets in Non-Premixed Counterflow Flames," *Proceedings of the Combustion Institute* **28** (2000) (in press).

[2] T. Noto, V. Babushok, A. Hamins, and W. Tsang, "Inhibition Effectiveness of Halogenated Compounds," *Combust. Flame* **112**(1-2) 147-160 (1998).

[3] D.J. Parks, N.J. Alvares, and D.G. Beason, "Fundamental Flame-speed Measurements in Combustion Gases Containing CF_3Br," *Fire Safety J.* **2**(4) 237-242 (1980).