Critical National Need Idea Title: *Drinking Water Health and Safety*

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ADVANCED TECHNOLOGIES FOR THE INFRASTRUCTURE:

DRINKING WATER HEALTH AND SAFETY

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Critical National Need: Sensor Networks for Municipal Water Systems

There is a need for a high density network of sensors deployed throughout a water distribution system that continuously monitors water quality in real time. Ideally the network would comprise of sensors that detect the presence, and the possible presence, of microbial contaminants responsible for pathogen borne pandemics. The CDC[1] reports that 4.26–11.69 million annual gastrointestinal cases (AGI; confidence interval unknown),[2] and a mean of 16.4 million annual AGI cases (range 5.47–32.80).[3] Of the reported cases of infections caused by tainted drinking water, approximately 66% were etiologic agents for influenza (viral infection) and E-Coli infections[4]. Recent public disclosures indicate insidious drug contaminations of our public water system. The EPA's vigilance over environmental safety has listed 13 heavy metal toxins and 40 carcinogenic compounds that should be routinely monitored in drinking water. Homeland Security is concerned and vigilant over public protection against terrorist activities and has listed neurotoxin contaminants among the dangerous agents to be monitored in our public water supplies. The challenge of monitoring water safety is daunting and such task that can only be addressed by the federal government.

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[1] 2006 National Estimate of Waterborne Disease Associated with Public Drinking Water

[2] Colford JM, Roy SL, Beach MJ, Hightower A, Shaw SE, Wade TJ. A review of household drinking water intervention trials and an approach to the estimation of endemic waterborne gastroenteritis in the United States. Journal of Water and Health 2006;4(Suppl 2):71-88.

[3] Messner M, Shaw S, Regli S, Rotert K, Blank V, Soller J. An approach for developing a national estimate of waterborne disease due to drinking water and a national estimate model application. Journal of Water and Health 2006;4(Suppl 2):201-40.

[4] Surveillance for Waterborne Disease and Outbreaks Associated with Drinking Water and Water not Intended for Drinking MMWR Surveill Summ. September 12, 2008 / 57(SS-9);39-69.

Problem Magnitude

The health and safety of municipal drinking water systems is critical to the national well being and prosperity. Water quality is not only a critical health problem that overburdens the public health system but it is a matter of national security. There is an increased public awareness for the dangers of contaminated water that is driving a $20+ billion bottled water industry world-wide. This industry will continue to grow at a torrid pace until utilities can win public confidence over the safety and quality of municipal drinking water. The challenge of municipalities is to improve water infrastructure to meet the demands for safe drinking water. The EPA estimates that US investment in water infrastructure will be $277 billion over the next 20 years. Such investment is dwarfed by the world-wide infrastructure investment need that includes underdeveloped countries and new burgeoning world economies.

Water has become a valuable commodity driven by an increasing demand for a limited resource. The world-wide water industry has been estimated by the American Water Works Association (AWWA) at $400 billion. The size of the domestic (USA) water market alone is about $95 billion, the drinking water segment comprising $13 billion and growing at a rate of 12% per year. Delivering drinking water to the public requires processing, purification and transport, all of which contribute to the cost. As is the case for crude oil, potable water is bound by the same economic principles of supply and demand and will surpass the value of oil as a valued commodity. Cheap abundant energy is necessary for a healthy economy but water is essential to life.

Safe drinking water is a national infrastructure issue that needs to be addressed by re-engineering our municipal distribution systems with improved pipelines and water purification/processing. Security, deterrence, purification, environmental wastewater monitoring and continuous water quality monitoring are all essential factors of a comprehensive “clean water” system that should be coordinated with industrial effluent cleanup and our national health care system. Water quality monitoring is the last line of defense for protecting the public health. Ideally, water monitoring should function like weather forecasting to predict the incidence of seepage into the distribution system. Pipeline breaches should be detected instantaneous, and with pinpoint accuracy for a seamless and publicly transparent response .

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Water monitoring is a critical component of any distribution system infrastructure plan because in spite of any safeguards in construction pipeline breaches do occur, whether they are caused by natural events or man-made. The problem is that currently available sensor technology is too expensive and ineffective. High risk advanced sensor technology and implementation systems are too expensive for private sector investment and the burden of compliance is a public matter and outside the realm of private enterprise. The private sector relationship to a public utility operation is likely to be similar to defense contractors. To be sure, the real time monitoring of EPA listed toxins and human pathogenic organisms is an extraordinary undertaking that requires high risk investment in advanced sensor technology. However, the problem is not insurmountable and there are strategies that can be effectively implemented. Chemical profiles or signatures are definable that are indicative of unsafe water. Also, not all EPA mandated contaminants require real time monitoring for detection, that is, heavy metals and carcinogenic compounds must be eradicated from the source but pathogenic organisms make people sick and must be neutralized immediately.

Societal Challenge

Chlorine is the predominant disinfectant used in our (USA) municipal water distribution systems. It is dispensed into our drinking water at the processing plant as a residual disinfectant additive prior to release into the distribution system. Chlorine is a strong oxidant that inactivates pathogenic organisms but it is also primarily responsible for the deterioration of water pipeline equipment. The disinfection chemistry of chlorine is both complex and time sensitive because its potency is entirely dependent on other water constituents. Therefore, disinfection chemistry must be profiled for all significant chemical parameters and recorded continuously for effective hazard detection. Other contaminants can actually be identified off-line with no significant detriment to hazard management. The EPA has placed new demands on utilities to institute systems that can respond immediately in an effort to mitigate water contamination. Current testing practices require multiple “grab” samples taken in the field, followed by laboratory analysis, with a minimum of 48-hour turn around time for the test results. However, such EPA regulation does not solve the problem because laboratory test results are not timely and hence, the information content of the analysis is typically erroneous or not “actionable”. What is needed is real time water monitors for chlorine and associated chemistry, ideally dispersed throughout the municipal distribution system. For example any sudden changes in chlorine concentration or related water chemistry (such as oxidation-reduction potential, pH, dissolved oxygen, conductivity, etc) would be indicative of introduction (intentional or natural) of contamination. Such a system would provide the immediate "event" detection and the location of such occurrence. However, a sensor network for a municipal water distribution system is cost prohibitive by today's product standards and availability. Commercial water monitors are based on technology adapted from the laboratory, making such monitors expensive and difficult to deploy into networks. This is so because of instrument calibration requirements and general maintenance that renders them expensive and impractical. For maintenance-free durable operation, the sensors must be resistant to the harsh corrosive conditions imposed by chlorinated water over extensive time periods.

Today's reality is that pipeline breaches are difficult to locate precisely and the typical response of the processing plant is to release more chlorine into the system, exacerbating the problem. While elevated chlorine levels might afford a greater margin of safety toward infection, it is also hazardous to human health and must be carefully controlled. Also of concern are the disinfection byproducts of chlorine that are mutagenic and thus, pose a health hazard to humans as well, albeit a delayed one. Ideally, the technology should pin point the location of the breach and the nature of the contamination with timely and precise information. It is important to not only inactivate pathogenic organisms but to do so with safe levels of chlorine and do it at the exact location of the pipeline breach with precise control because the indiscriminate use of high chlorine levels throughout the distribution system subjects people to toxic chlorine levels and byproducts of chlorination.

Also of importance is managing the effect of a pipeline breach on the community. During the process of managing containment and recovery, it is equally important to unambiguously announce to the public when water is or is not safe to drink by basing decisions on timely site test verification data. The ability to accurately monitor drinking water systems, in real time and throughout the distribution system, with cost efficient high density sensor networks strikes at the very core of what we recognize as a critical national need. There is no debate here, the ambiguities lie simply on identifying which technologies meet the criteria for functionality and pragmatism that satisfy the needs for water quality and safety.

The key criterion for such monitoring technology is the ability to deliver cost effective actionable information to utilities. This translates into durable sensors that will function reliably for months without maintenance of the sensor network. Durability is associated with corrosion resistance of the sensor coatings which must remain active and stable in use for months at a time and also maintain a stable shelf life that ensures a reliable commercial supply. Nanostructured materials technology is the likely solution to stability and durability issues of sensors. Potentially disruptive technology must also be embraced by the utilities in order to gain credibility and strive to effect seamless adaptation. The likely sensor system “chip” integrates active circuitry for measurement and digital signal processing. The integrated sensing device package will include local intelligence and wireless communication, all comprised within a small footprint requiring low power consumption or self powered by energy scavenging technology and compatible with remote location deployment. This will enable on chip signature analysis and data reduction for complex analysis (i.e., pattern recognition) and results reporting for archival storage. A network architecture comprised of “smart” sensor nodes is not only more efficient in information processing and storage, but more importantly, it is also lowest in system cost because it simplifies central hub computation and communication requirements.

The sensors enable the network, but the network empowers an entirely new set of functions. Geographic and temporal information projections of water quality can now be realized to enable forecasts of contamination events and interpolate causes. Local information processing capability enables systematic chemical signature analysis and simplifies data reduction and archival storage of information. A reduced data processing burden at the central hub accelerates communication traffic and frees up the hub to perform other logic and control functions. Such network architecture with intelligent sensor nodes enables more intense computing of holographic trend analysis and forecasting as a predictive tool of events in much the same manner as we employ weather forecasting. The envisioned system architecture decouples the sensor platform design evolution and node capability from network system capability so that as additional sensor parameters come on line, node information content and analytical quality are independently improved. Such additional capability would include more chemical constituents (e.g., heavy metals), toxins and pathogenic organisms. Similarly, the growth of the network is more easily managed if hardware and software are decoupled. As the network grows extensively (more information content) and intensively (node density) the geographic and temporal forecasting software is designed to assimilate all the nodes analytical content and algorithms. This proposed technology development scheme and network architecture is cost effective and allows the sensors and the network to develop independently.

Interaction of Critical National Need and Societal Challenges

The ideal monitoring location for any high density network is at the point of use. Sensor deployment at the water meter point of entry of a residential home is most desirable. The public needs to know the source of contaminants and be able to isolate external from internal events so that water treatment and controls can be effectively implemented. The home of the future will likely comprise a sensor monitoring network system (water and air quality, security, appliance controls, communications and energy). The commercial benefits of sensor network and communication technology extends well beyond drinking water monitoring for public health and safety and will benefit our national competitiveness and strengthen our economy.

Mapping to National Objectives

The nation's drinking water and wastewater infrastructure is aging, with some more than 100 years old. The growth in population will place an added stress on this aging infrastructure. The current treatment and management strategies are not designed for emerging issues (e.g. emerging contaminants). Investments in research and development have declined, and significant investments in infrastructure are unlikely to occur any time soon.

The EPA (Clean Water and Drinking Water Infrastructure Gap Analysis, 2002) reports a potential for funding shortfall in excess of $500 billion by 2020 for drinking water and wastewater infrastructure at current levels of investment in capital equipment, operations and maintenance. In this Gap analysis, EPA considered 54,000 community water systems, 21,410 non-community water systems and 16,000 publicly owned water treatment works. The Office of Water of EPA has launched a Sustainable Water Infrastructure initiative. Under this initiative, EPA is working with stakeholders for the adoption of new management approaches by utilities, and is supporting research and development of new technologies and strategies in an effort to make the current system more efficient.

On October 29, 2008, representatives of American Society of Civil Engineering (ASCE) will testify before the US Congress (House Ways and Means Committee; and House Transportation and Infrastructure Committee) on infrastructure and economic recovery initiatives. The Commonwealth of Pennsylvania has included a referendum on the November 2008 Presidential election ballot - a $400 million Clean Water Referendum, which if approved will provide municipalities with the funding to repair and upgrade their vital water infrastructure. It is estimated that the Commonwealth would need over $36.5 billion over the next 20 years to maintain reliable water service. These are some of the many examples of efforts underway to address this national issue.

This White Paper proposes the creation of a national Center to provide innovative and cost effective technologies to assist municipalities meet this growing challenge. The proposed Center would provide technology, guidance and information to the municipalities. The Center would focus on current and long term water infrastructure needs, and continuously evolve to map its focus and vision in line with national needs. Modernizing our aging infrastructure is likely to span a decade or more, so it is essential that we deploy cost effective monitoring technology to the existing systems while we design the appropriate architectures for the future. The Center would provide both a support system for today's reality and a bridge to a modernized water infrastructure.

The proposed technology focus is a flexible platform of sensor and communication technologies that could be adapted and applied for continuous monitoring of the water and wastewater infrastructure. With the advancement in science and technology, the technology platform is expected to be continuously upgraded. It will also serve as an information resource for nation's water and wastewater utilities, government, academia and other stakeholders. Some of the platform technologies to be investigated would include: nano-structural materials/ nanotechnology, catalysis science, DNA diagnostics for pathogenic ID, immuno-diagnostics, nano-wire antennae detectors, electrochemical detectors, surface plasmon resonance detectors, wave guide sensors, acoustic sensors, NEMS/MEMS, micro-fluidic systems, self- energized systems, wireless communication, pattern analysis & forecasting, signature analysis software, amongst others. A consortium of Universities and technology companies will participate to support the technology platform. The mission of a currently proposed National Science Foundation (NSF) Industry/University Cooperative Center on Water and

Environmental Technology (WET) located at Temple University, University of Arizona and Arizona State University, is aligned with the focus of this White Paper. The NSF has granted a Planning Grant towards the establishment of this WET Center. The WET NSF Center will complement the Center proposed in this White Paper. The Commonwealth of Pennsylvania recently (October 2008) established a Pennsylvania Environmental Technology (PET) Center (with initial seed funding of $1.6 million) at Temple University; and this state wide PET center will complement the proposed Center on drinking water infrastructure monitoring.

In addition to developing, testing and identifying technologies consistent with sensor networks, the proposed Center will also have a primary goal to commercialize the technologies by engaging industrial partnerships. The need for sensor technology is ubiquitous throughout the beverage, foods and industrial processing and manufacturing of semiconductors, pharmaceuticals, etc. It is anticipated that a number of municipalities and industries will participate in the Center and become partners in research.

Hence, the proposed Center is expected to have a profound impact not only in the development of transformative technologies but also by providing technological assistance to the nation's water municipalities for rapid detection of failures in the water distribution system. A number of stakeholders including NIST and other government agencies, municipalities, private water companies, technology providers, academia are expected to work collaboratively in the Center.

TIP's Role

Local and state government is empowered to enable infrastructure investment that addresses the needs of its constituents. While water infrastructure is recognized as a critical component of economic development and an attribute of a thriving commercial environment, state government is not equipped to engage in transformational technologies. The Commonwealth of Pennsylvania, for example, funds translational technology that enables local industry through technology investment grants and non-recourse loans to assist businesses engage in infrastructure (e.g. sensors) technology. Ben Franklin Technology Partners (BFTP) of South Eastern PA is an agent of the Commonwealth that facilitates technology investments. BFTP's role as a WET-Temple partner is to facilitate commercialization of the technology developed by the WET program. BFTP is also an agent for the development of transformative technology *via.* its partnership with the Nanotechnology Institute led by U. of Penn and

Drexel and funded by the Commonwealth of PA. It is imperative that state and federal resources be leveraged to access such disruptive technologies *via* Federal Science and Technology agencies (e.g. NIST). The Commonwealth recognizes the need to participate in regional initiatives (e.g., Mid-Atlantic Nanotechnology Alliance or MANA) that promote regional academic and industry cluster competencies in such areas as nanotechnology and catalysis science. Such regional competency clusters are ideally positioned to lead innovation thrusts in technologies of National priority. With Temple University's leadership in the Industry/University Cooperative Center on Water and Environmental Technology (WET), partnering regional universities that would collaborate is this effort would include U. of Penn Drexel and U. of DE.

The role of NIST is to enable the commercialization of transformational technology and promote Venture Capital deal flow. Sustainable technology development is best achieved with industry participation in goal setting and commitment to the commercialization process. The ideal role for NIST is to mount a coordinated effort with NSF or EPA programs to develop the next generation of sensor network systems. NIST's critical role is to enable the manufacturing technology and to leverage National Labs participation in the academic program.