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White Paper on Improvement of Structural Integrity Monitoring for Drinking Water Mains

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by

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Sally Gutierrez, Acting Director
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Abstract

The improvement of water main structural integrity monitoring (SIM) capability as an approach for reducing high risk drinking water main breaks and inefficient maintenance scheduling is explored in this white paper. Inadequate SIM capability for water mains can cause repair, rehabilitation, or replacement (R^3) to be scheduled either late or early. Late R^3 can allow serious deterioration, main breaks, and their associated consequences to occur. Early R^3 is inefficient, which adversely affects system maintenance priorities and economics. Existing SIM technologies inadequately characterize various combinations of pipe materials, configurations, and failure modes. Fortunately, substantial research to improve SIM is underway or planned, but mostly for high risk, non-drinking water applications. A systematic effort by EPA and other Federal agencies, in cooperation with relevant stakeholders, is recommended to identify, prioritize, and capitalize on opportunities to accelerate SIM capability improvement. Acceleration of SIM improvement research is especially important at this time, since: (1) for the next 30+ years a steep rise in R^3 decision-making is projected for our aging water mains; (2) multiple technology transfer, collaboration, and leveraging opportunities exist; and, (3) SIM capability improvement takes time.

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Acronyms and Abbreviations

)P	change in probability of a pipe failure
ABPA	American Backflow Prevention Association
AC	asbestos concrete
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
B	benefit
C	cost
CBO	Congressional Budget Office
CF	consequences of failure
CI	cast iron
DI	ductile iron
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ECCP	electrically conductive composite pipe
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification program (EPA)
F	coverage by inspection (temporal, spatial, or failure mode)
FLC	Federal Laboratory Consortium
FRP	fiber glass reinforced plastic
GSA	General Services Administration
HDPE	high density polyethylene
ICP	instrumented cathodic protection
MFL	magnetic flux leakage
MILI	mobile, in-line inspection
MNII	mobile, non-intrusive inspection
NASA	National Aeronautics and Space Administration
NCER	National Center for Environmental Research
NDE	nondestructive evaluation
NETL	National Energy Technology Laboratory (DOE)
NHSRC	National Homeland Security Research Center
NIST	National Institute of Standards and Technology
NRMRL	National Risk Management Research Laboratory (EPA)
NSF	National Science Foundation
NTIAC	Nondestructive Testing Information Analysis Center (DOD)
OPS	Office of Pipeline Safety (DOT)
ORD	Office of Research and Development (EPA)
ORNL	Oak Ridge National Laboratory (DOE)
OSP	Office of Science Policy (EPA)

P	probability of pipe failure
PCCP	prestressed concrete cylinder pipe
PE	polyethylene
POD	probability of detection of a critical flaw
PTA	pipeline test apparatus (EPA Facility, Edison, NJ)
PVC	polyvinyl chloride
R^3	repair, rehabilitation, or replacement
R,D,T,&V	research, development, testing, and verification
RFP	request for proposals
S	steel
SBIR	Small Business Innovation Research program (multiple agencies)
SCA	structural condition assessment
SCADA	supervisory control and data acquisition
SCNGO	Strategic Center for Natural Gas and Oil (DOE)
SIM	structural integrity monitoring
USBR	U.S. Bureau of Reclamation
UWMB	Urban Watershed Management Branch (EPA)
V	value
Vc	critical value
WERF	Water Environment Research Foundation
WSWRD	Water Supply and Water Resources Division (EPA)

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Section 1: Introduction

The improvement of water main structural integrity monitoring (SIM) capability as an approach for reducing high risk drinking water main breaks and inefficient maintenance scheduling is explored in this white paper. Structural integrity[1] of water mains[2] refers to the soundness of the pipe wall and joints for conveying water to its intended locations and preventing egress of water, loss of pressure, and entry of contaminants. SIM is the systematic detection, location, and quantification of pipe wall and pipe joint damage and deterioration (e.g., wall thinning, cracking, bending, crushing, mis-alignment, or joint separation) of installed drinking water mains. Effective SIM enables determination of the present condition and the deterioration rate of the pipe. Present condition for a particular pipe location is determined by a single measurement of a structural parameter. Deterioration rate for a particular pipe location is determined by periodic measurement of a structural parameter. If the measured parameter reaches a pre-determined unacceptable level, then actions can be taken such as (a) small repairs to forestall accelerated deterioration, and much larger repairs later or (b) repair, rehabilitation, or replacement (R^3) to prevent failures and associated damages. Conversely, if a measured parameter is at an acceptable level, then R^3 can be safely deferred. If suitable failure models exist, SIM data on present condition and deterioration rate may also be useful for estimating future structural condition and remaining service life, and for optimizing inspection frequencies.

Problem summary

The lack of cost-effective SIM capability for water mains can cause R^3 to be scheduled either too early or too late. Either error can cause adverse effects.

- Late scheduling of R^3 can occur when sparse or inaccurate structural integrity data cause under-estimation of pipe deterioration and/or loading. Late scheduling of R^3 allows potentially preventable main breaks to occur. Particularly undesirable are high risk main breaks, which can cause: (1) sudden and significant losses of water and pressure, (2) serious health or drinking water quality effects to customers, (3) other adverse effects to critical customers, or (4)

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[1] Excluded from consideration here are tuberculation and scale formation that clog the bore of the pipe, leaching of pipe or liner constituents into the water, and permeation of contaminants through the pipe wall, coatings, linings, or gaskets. Also excluded is the structural integrity of pumps or valves.

[2] "Water mains" refer here to raw water transmission mains and treated water transmission, arterial, or distribution water mains, but not service lines. A raw water transmission main transports raw water from source to the treatment plant. A treated water transmission main transports water from the plant to storage or directly to an arterial main. Arterial mains transport treated water to the distribution mains from the treatment plant or storage. The distribution mains transport water to the service lines, which transport the water to the end user. For a given system the transmission mains are typically larger in diameter, straighter, and have fewer connections than the distribution mains (Smith et al., 2000).

major damage to the surroundings. A key premise of this paper is that high risk main breaks can be reduced by monitoring pipe deterioration more frequently, comprehensively, and/or accurately, and then using the collected data to generate more accurate and timely scheduling of pre-failure R^3.

- Premature scheduling of R^3 can occur when an inadequate quantity or quality of structural integrity data causes decision-makers to over-estimate the areal extent and or/the severity of pipe deterioration. If the actual condition of the pipe can be accurately determined by inspection, then selective R^3 on a small fraction of the pipe becomes an option when it is the more economical way to address the problem.
- Both the cost of high risk main failures and the inefficiency of premature replacement exacerbate the funding gap between current and required spending for capital, operating, and maintenance expenditures. The size of the funding gap has been estimated by EPA at $45 billion to $263 billion (i.e., approximately $2.3 billion to $13 billion per year) for the 20-year period from 2000 to 2019. (U.S. EPA, 2002, b & c; Congressional Budget Office (CBO), 2002)

Numerous SIM options already exist for drinking water mains, but these options have many shortcomings. Various combinations of pipe materials, configurations, and failure modes are not adequately or economically characterized by existing SIM technology.

A substantial amount of research, development, testing, and verification (R,D,T,&V) is underway or planned for improving SIM, but most of the effort is directed toward high risk, non-drinking water applications. Example applications include oil and natural gas pipelines, nuclear power plants, large buildings, bridges, and aircraft. A significant amount of this research is government-sponsored. Many of these SIM improvement efforts involve applying recent advances in technology to the creation of better, cheaper, and faster ways of acquiring and analyzing structural integrity data. The products, data, and procedures from some of this R,D,T,&V are a relatively untapped source of technology transfer opportunities for water main SIM improvements, but there is no systematic effort to identify, prioritize, and capitalize on these opportunities by the federal government, and in particular the EPA.

Acceleration of the SIM improvement process is important, since: (1) SIM capability improvement is a difficult, uncertain, slow, tedious, and expensive process; and (2) a substantial portion of the transmission and distribution system is projected to be approaching or reaching the end of its service life. The need for decisions to implement or delay replacement will be greatly increasing between now and approximately 2035, when the annual replacement rate is projected to peak at about 2% (i.e., 16,000 to 20,000 miles of pipe replaced/year), which is more than four times the current replacement rate. (U.S. EPA, 2002 b and c)

Resources are limited, so it is important for the drinking water community, including the federal government, to define and prioritize drinking water mains SIM capability improvement needs, and cooperate and collaborate to complete the required R,D,T,&V activities.

Scope of the white paper

Prevention of main breaks is emphasized over prevention of main leaks. The adverse economic effects of main breaks (e.g., damages, disruption of business and traffic, and emergency response costs) and potential for health effects (e.g., potential contaminant intrusion or backflow due to pressure loss) appear to be more immediate and severe, and more likely to be linked to a specific main break incident than for main leaks. Although more water is probably lost from leaks than from main breaks, leaks are often tolerated for a variety of reasons.

To the extent that main leaks can serve as a reliable indication of the location and timing of future main breaks, the detection, location, and quantification of main leaks is relevant to pre-failure detection, location, and prevention of main breaks. However, detection of pipe leaks is not specifically addressed here, because it is covered in other documents (e.g., O'Day et al., 1986; Makar and Chagnon, 1999; Smith et al., 2000; Jackson et al., 1992; Tafuri, 2000; Hunaidi et al.,1999).

Although improvement of structural condition assessment (SCA) is closely related to improvement of SIM, SCA is excluded, to the extent feasible, from the scope of this white paper. SCA is the determination of the present and future fitness-for-service of the pipe. It will be assumed that adequate SCA for at least the imminent failure case is, or will become, feasible for some indicators and situations (e.g., corrosion pitting (Rajani and Makar, 2000), severe wall thinning, cross section deflection, misalignment, or bending). Inspection without effective condition assessment limits the value of the inspection to identification of failures that are either existing or obviously imminent. Condition assessment requires inspection data and is affected by inspection data accuracy. Although SCA improvement is excluded from this white paper, research on the topic is recommended to add value to current and future SIM capability.

Integration of SIM with hydraulic and water quality monitoring in the distribution system is a desirable goal. Although this is a potential future research goal, it is beyond the scope of this white paper.

Section 2: Detailed Problem Statement

This section describes: (1) water main breaks and their causes and risks, (2) the difficulties in inspection of buried water mains, and (3) the shortcomings of existing SIM capability.

Description, causes, and risks of water main breaks

A water main break is the structural failure of the barrel or bell of the pipe. Types of water main breaks include: (1) circumferential breaks; (2) longitudinal breaks; (3) holes caused by either corrosion or pressure/blowout; (4) split bells, including bell failure from sulphur compound joint materials; (5) sheared bells; and, (6) spiral cracks (O'Day et al., 1986; Makar et al., 2001). Water main breaks typically produce a substantial loss of pressure and flow at the point of the break and possibly elsewhere in the system, and therefore tend to be readily detectable and require immediate attention. In contrast, water main leaks often produce smaller, less easily detected, and less disruptive changes in pressure and flow that may go undetected and/or uncorrected for some time. The distinction between a large leak and a main break is often unclear.

Water main breaks are caused when and where the loading on the pipe exceeds the pipe strength (i.e., ability to resist loading). Corrosion is a major cause of pipe strength deterioration. There are multiple causes of corrosion. Corrosion can occur on either the interior or exterior of the pipe. Manufacturing flaws can also contribute to pipe strength deterioration. Numerous types of loading can contribute to weakening the pipe or causing failure. Multiple factors may act together to cause failure (O'Day et al., 1986; Makar et al., 2001). Table 1 provides a more extensive list of factors that contribute to pipe failures.

The risk posed by a main break is the product of the consequences and the probability of failure. Only low risk (i.e., low probability and consequences) and high risk (i.e., high probability and consequences) situations will be discussed immediately below. High risk main breaks are the predominant focus of the report. Intermediate risk situations will require an appropriate blend of the high and low risk approaches for scheduling R^3.

Table 1.	Main Break Occurrence Factors
Chemical Stressors	Internal & external corrosion caused by factors such as aggressive water or soil, microbes, stray currents, oxygen gradients, & bimetallic connections
Physical Stressors	Damage during transport, unloading, storage, & installation Traffic loads Soil loads from differential settling caused by bedding washout from water leakage, drought, expansive clays, & landslides Point loads from projecting rocks, etc. Internal, radial loads from water pressure fluctuations Axial loads from seismic activity, soil movement, & water hammer Thermal stress from temperature differences between water, pipe, & soil; freezing/expansion of water; & soil frost loads Damage by excavating equipment that causes or accelerates failure Damage to external coatings or internal linings that enables accelerated corrosion
Other Factors	Aging (i.e., the accumulation of effects over time from external chemical & physical stressors & from equilibrium reactions within the pipe (e.g., brittleness)) Pipe flaws arising from design, raw materials, manufacturing, or installation errors

- Prevention of low risk main breaks is not a high priority, since the benefits of prevention are likely to be much less than the cost of prevention. The benefit of preventing a low risk main break by SIM is small (i.e., the avoidance of the minor adverse effects of an event that is unlikely to occur). The costs of preventing a main break include the inspection cost (e.g., mobilization to/from an inspection site; pipe preparation and return to service; data collection, storage, transmission, analysis, and reporting); selection of the time, location of R^3 actions; and implementing the R^3 actions. Hence, the cost of preventing a low risk main break is likely to exceed its benefit. Therefore, for low risk main breaks, the focus tends to be on post-failure repair of the main until the frequency of failure becomes so high that it is more economical to replace the pipe, rather than continue to repair it. Procedures for calculating the optimum number of breaks before replacements are available (e.g., O’Day et al., 1986).

- For high risk mains the effects of even a single main break are serious, so prevention becomes much more desirable. The ability to prioritize and schedule R^3 based on pipe condition can be especially valuable for systems that have a substantial amount of high-consequence pipes that are approaching the ends of their service lives, but also have insufficient funds to address all the deteriorated pipes at one time. In this situation, the order in which pipes are repaired, rehabilitated, or replaced is very important, because the number of failures and their adverse effects can be minimized by first addressing the pipes that are in the worst condition and have the highest probability of failure. The development of more effective and efficient inspection capabilities helps support “worst-condition pipes first” scheduling of R^3 and reduces the number of failures and their adverse effects. Table 2 lists a number of potential high consequence main situations.

Table 2. Example High Consequence Main Break Scenarios

Critical Customers	Large population Fire protection Key industry/defense/government site	Hospital Limited alternative supply
Critical Surroundings	Industrial/commercial/residential Highway/bridge/tunnel/railroad/subway/airport Critical water main/sewer/communication Energy pipeline/cable	
Difficult Response	Large main Difficult terrain Heavy traffic	Remote site River crossing Extreme temperatures

Water main breaks cause a range of adverse effects. Table 3 summarizes the types of adverse effects that can be caused by main breaks. The first column lists adverse effects that relate to public health and the environment, and many are relevant to EPA’s mission and programs. Of particular concern is the potential loss of pressure following a main break, which can allow entry of contaminants, either at the break location or at more distant locations by back-siphonage through cross-connections to contaminated sources (American Water Works Association (AWWA), 2002). The second column in Table 3 addresses adverse economic effects, which can have indirect or delayed, but important, effects on distribution system structural integrity, and ultimately public health and the environment. Adverse economic effects on utilities can affect drinking water quality by causing deferrals of needed capital and maintenance expenditures, and by further increasing the infrastructure funding gap. Appendix 1 lists 14 examples of some recent (1996 to present) high consequence main breaks. Improved SIM capability enables utilities to more effectively manage their water mains, which represent more than 50% of the value of their assets.

Table 3. Types of Adverse Effects from Water Main Breaks		
Health and Environment	**Economic**	**Safety & Inconvenience**
Public Health Problems Waterborne disease outbreaks Low pressure • Presumptive boil water notices Noncompliance • Primary WQ standards Loss of drinking/bathing water Loss of water for sewage Sewer overflows from flooding	**DW Utility** Lost revenue Response costs System damages/repairs Claims Deferral of maintenance	**Public Safety** Fire fighting water loss Worker hazards Traffic accidents • Flooding • Icing • Disruption Electrical shock hazards
Other Water Quality Problems Noncompliance • Secondary WQ standards **Resource Depletion** • Water • Energy **Environmental Degradation** • Chlorinated water discharged to sensitive areas	**Non-DW Utility** Property damage • Residential • Commercial • Industrial Walk-in business losses Production losses Infrastructure Damages/outages • Electric/gas/steam • Sewer • Communication • Road/tunnel/bridge • Train/subway/airport	**Public Inconvenience** During main break During remediation

Water main breaks can also cause serious adverse effects to public safety (e.g., loss of firefighting water and pressure, flooding, and icing) and convenience. The third column in Table 3 lists additional adverse effects of water main breaks on public safety and convenience. Preventing these types of adverse effects is not part of EPA's clean and safe water goals. However, since water main breaks are a common cause of both water quality and public safety problems, there is some potential for research collaboration between EPA and public safety research organizations.

Table 4 summarizes the data, identified in this study, that link water main breaks to adverse effects on drinking water quality. A relatively small number of documented incidents (17) were identified over a 25-year period. The most severe incident, which occurred in 1989 in Cabool, Missouri, resulted in 4 deaths, 32 hospitalizations, and 243 illnesses (Craun and Calderon, 2001). The actual number of main break incidents that adversely affected water quality certainly exceeds the number of documented incidents, but no quantitative estimates of the ratio of documented to actual incidents were found or developed. There are several reasons for the difference between the documented and actual number of incidents. "There are many backflow incidents which occur that are not reported" (AWWA, 1995). It is often difficult to link contaminant entry to a specific main break incident, since the identity and entry point of the contaminant may not be known;

the contamination event may be of limited duration and volume, and probably difficult to track; the presence of the contaminants or harmful effects may not be immediately detectable by the consumer (e.g., pathogens, carcinogens); and there may be multiple possible sources. Also, when there is a main break, efforts may tend to focus on responding to the main break and any problems associated with it, as opposed to searching for potential backflow.

One study cited in Table 4 lends support to the hypothesis that the actual number of drinking water quality incidents exceeds the documented number of incidents. A survey of 70 systems found about 2100 pressure reduction incidents caused by main breaks in a one-year period. Pressure reduction can, when there are unprotected cross-connections to contaminated sources and the pressure reduction is of sufficient magnitude, enable backflow of contaminants into the system. Some utilities issue boil water notices for sectors affected by main breaks based on the assumption that the potential for loss of pressure increases the possibility that contamination may enter the system. Two other studies (American Water Works Association Research Foundation (AwwaRF) projects (No. 436 (Kirmeyer et al., 2001)), and No. 2686 in progress) are examining transient, reduced-pressure waves that are caused by water velocity changes from the main break, or by emergency valve closures in response to the break. These studies should provide data regarding the probability that these transient low-pressure incidents are enabling contaminants to enter the distribution system through holes or cracks in the pipe. Reduced-pressure transients and the resultant inflow may occur at a considerable distance from the main break, valve closure, or other cause of the pressure transient. Deteriorating wastewater collection systems are a potential source of

Table 4. Summary of Main Break Incidents Affecting Drinking Water Quality

Mechanism	Description
Contaminant entry at or near break site	E. Coli contamination from sewage overflows enters mains via breaks and meter replacements – 4 deaths, 32 hospitalized, 232 illnesses; Cabool, MO, 1989 (Craun and Calderon, 2001)
Backflow of contaminants due to pressure loss	17 contamination backflow incidents listed as due to main breaks (1969 to 1994) (AWWA, 1995)
	Many backflow incidents not reported (AWWA, 1995)
Pressure reduction incidents from main breaks	“A survey of 70 systems reported 11,186 pressure reduction incidents in the past year... 19.2 % were due to main breaks, and 16.2 % of incidents were due to service line breaks (ABPA, 2000). Hills and other elevations compound pressure loss effects caused by main breaks, fire flows, and other events (ABPA, 2000).” (U.S. EPA, 2002a)

Table 4. Continued	
Potential for intrusion of contaminants due to pressure transients	AwwaRF evaluations of occurrence and duration of low pressure transients - Microbial contamination of trench water demonstrated - Occurrence of low-pressure transients demonstrated - Potential intrusion volumes calculated - Risk assessment not complete (Kirmeyer et al., 2001; AwwaRF No. 2686, in progress)
Boil water advisories due to pressure loss caused by a main break	Data collection not attempted for this project
Boil water notices due to confirmed contamination after main-break-caused pressure loss	Data collection not attempted for this project
Acceleration or reversal of flow, mobilizes sediment, biofilm, and associated chemical or biological contaminants.	Mobilization of solids is known to occur, but data collection not attempted for this project to determine extent of water quality effects and associated health risks

contaminants that could be drawn into water mains during low pressure incidents. Main breaks may also accelerate and/or reverse the flow rate, which can disturb sediment or shear biofilm from the pipe wall, mobilizing not only the sediment and biofilm, but any associated chemical or biological contaminants. A further effect of acceleration or reversal of flow due to main breaks is water hammer, which may cause cracks or holes at other points in the system, which could contribute to the occurrence of the two trench water contamination scenarios described above.

Magnitude of the water main break problem

This section presents statistics indicative of the magnitude of the main break problem in the United States. This section does not address the number of main breaks by risk class, material, diameter, failure mode, or preventability by SIM devices.

A 1994 estimate placed the number of main breaks in the United States at 237,600/year (Kirmeyer et al.,1994). This estimate was based on an estimated total length of water mains in the United States of 880,000 miles (excluding service lines) and a rate of 27 main breaks/100 miles/year. Variation is considerable between utilities. In one survey, main break repair rates ranged from 7.6 to 38.1 main break repairs/100 miles/year for 4 utilities. Seasonal variations in main break rates also occur, and northern cities tend to experience a substantial increase in main breaks during winter months. Data from surveys of limited numbers of individual utilities indicate a mixture of increasing, declining, and steady break rates. Based on the projected overall increase in the age of the U.S. distribution system piping and the substantial portion of it that is in either fair or poor condition, it can be inferred that the main break rate should be increasing. Approximately 29% of the United States' drinking water distribution system pipe was estimated in 1992 to be in fair (26%) or poor (3%) condition (Kirmeyer et al., 1994). How fast the 26% in the "fair" category will be joining the "poor" category is unclear. The pipe replacement rate of about 0.5% (Kirmeyer et al., 1994), if continued, will result in an average service life of 200 years, which is well beyond the typical design service lives of 50 to 100 years. The wastewater infrastructure also has deterioration problems, which will increase the probability of water main and sewer breaks occurring in close proximity. On the positive side, expansion of expenditures from the Drinking Water State Revolving Fund (DWSRF) and utilities for infrastructure rehabilitation and replacement, increased emphasis on efficient asset management, and more extensive use of pipe rehabilitation should help to reduce failure rates for the systems affected. Several new factors may affect main break rates in the future, such as the long-term structural integrity of pipe laid by new installation techniques and of pipe rehabilitated by new methods. There are also significant differences in pipe material (e.g., a tendency to use more polymer pipe), coating, and lining materials that may affect (positively or negatively) long-term main break rates. Even changes in disinfectants may have some effect (positive or negative) on long-term structural integrity.

The need for improved SIM technology

Numerous SIM methods have been developed over the years. Table 5 places SIM technologies into 12 groups and lists some their key weaknesses. SIM technologies are described in more detail in other documents (e.g., Dingus, et al., 2002; Tafuri et al., 2001; Stone et al., 2002; Cromwell et al., 2001; O'Day et al., 1986; Deb et al., 2002; Lawrence, 2001; Fennell and Lawrence, 2000; Jackson et al., 1992; Hunaidi et al., 1999; Rajani et al., 2000; Smith et al., 2000; Bickerstaff et al., 2002).

Current SIM approaches have serious limitations for water mains, especially if buried. Hence, structural integrity failures are often addressed by reactive maintenance, which is initiated after detection of an indicator of a structural failure (e.g., water spout; loss of pressure, volume or quality). Reactive maintenance must often be done under unfavorable weather, lighting, traffic, and/or schedule conditions. Repairs done under adverse conditions (e.g., water filled trench) may allow contaminated water to enter the pipe. In spite of the potential adverse health and economic consequences of reactive maintenance following failures, there may not be a technically or economically suitable alternative at the present time. Even where preventive maintenance, rehabilitation, and replacement programs are in place, their efficiency and effectiveness are hampered by the difficulty of accessing the system and efficiently inspecting it.

Table 5. Performance Weaknesses of Structural Integrity Monitoring Approaches

No.	SIM Approach	Weaknesses (see key below the table)									
		1	2	3	4	5	6	7	8	9	10
1	React (respond, repair/replace/rehab, cleanup) after failure	Y	N	?	N	N	N	N	Y	?	N
2	Monitor water quality (e.g., taste, odor, color, residual chlorine, microorganisms, composition, outbreaks)	Y	Y	?	N	Y	Y	Y	?	?	N
3	Excavate & inspect outer pipe surface	N	N	Y	N	Y	Y	Y	N	?	N
4	Excavate & remove pipe samples for evaluation	?	?	Y	Y	Y	Y	Y	?	?	N
5	Insert/remove & monitor coupons of pipe materials	?	?	?	Y	Y	Y	Y	?	?	N
6	Monitor hydraulic parameters (pressure, flow, roughness)	Y	Y	?	N	?	?	Y	?	?	N
7	Flaw detection & location by temporary, immobile sensors (e.g., acoustic emissions for leaks or PCCP wire breaks)	Y	N	Y	N	Y	Y	Y	?	?	N
8	Leak detection & location by external, remote sensing (e.g., aerial or satellite) surveillance	Y	N	N	N	Y	N	Y	?	Y	N
9	Intrusive, intermittent, close-range inspection methods (e.g., pigs with physical, optical, acoustic, ultrasonic, eddy current, or magnetic flux leakage measurement assemblies)	N	N	Y	Y	Y	Y	Y	?	?	N
10	Cathodic protection	N	N	N	N	N	Y	Y	N	N	N
11	Statistical evaluation of pipe characteristics, failure histories, maintenance records, and environmental conditions to generate repair/replace priorities	Y	?	N	N	Y	N	N	?	?	N
12	Establish and monitor sensing layer (e.g., instrumented cathodic protection, electrically conductive composite pipe)	N	N	?	N	N	?	Y	?	?	Y

Key	N = Not a weakness; Y = Yes, it is a weakness; ? = Uncertain whether it is a weakness or it depends on the situation.		
1	Only applicable to post-leak or break detection, not prevention	6	Incomplete spatial coverage – not applicable to all sections or components of system, configurations, or ambient conditions
2	Detects problem but does not efficiently locate it	7	Incomplete failure mode coverage –not applicable to all failure mode indicators (e.g., wall thinning, cracking, holes, leaks, & corrosion)
3	Labor intensive & slow	8	Inaccurate or unreliable determination of current structural condition
4	Requires intrusion into system	9	Inability to utilize the data to forecast residual service life
5	Incomplete temporal coverage – non-continuous inspection may miss short-term deterioration events (e.g., wire breaks)	10	Still in development

Section 3: Public Benefits from SIM Improvements

Improving SIM capability through R,D,T,&V is a proactive, cooperative, flexible approach to accomplishing a number of EPA's short-term and long-term drinking water protection goals. Reducing main breaks supports the Safe Drinking Water Act's goals of protecting public health and drinking water quality. Reducing main breaks, optimizing maintenance planning, extending infrastructure service lives, and reducing water leakage supports EPA goals of reducing the infrastructure funding gap and improving utilities' infrastructure management capability. Table 6 links the benefits of SIM capability improvement to the associated EPA goal areas.

A rigorous determination of the economic benefits from main break prevention was not within the scope of this white paper. However, it is a relevant question, and so a conceptual estimate of the potential economic benefits from main break prevention was generated as a starting point for further consideration. Based on the assumptions shown in Table 7, it was estimated that $2.4 billion in losses could occur annually from high consequence main breaks. If 20% of these high consequence main breaks could be prevented, then $480 million/yr in losses could be prevented. Again, based on the assumptions in Table 7, an acceptable inspection cost rate was estimated at $54,000/mi/yr (approximately $10/ft/yr).

A rigorous determination of the number of each type of main break that could be prevented was not attempted. However, as was done for economic benefits, a conceptual estimate was generated as a basis for further discussion. Each of the approximately 240,000 water main breaks that occur in the U.S. each year has some potential for causing adverse health, water quality, economic or other effects. Not all of these main breaks are preventable for a variety of technical, risk, and economic reasons, and the majority will probably not cause major adverse effects. However, if, for example, 10% of main breaks can be prevented through improved SIM, then this will reduce main breaks by about 24,000/yr, which is a significant number, even if it doesn't completely eliminate the problem. More important than simply reducing the number of main breaks is reducing the risk they pose. If classes of high risk main breaks are focused upon and are successfully prevented, then the overall risk from main breaks could be substantially reduced by preventing a relatively small fraction of main breaks.

Table 6. Functional & Program Benefits of Effective & Affordable Inspection

FUNCTIONAL BENEFITS OF EFFECTIVE AND AFFORDABLE INSPECTION	PROGRAM BENEFITS			
	Drinking Water Quality Protection		Infrastructure Funding Gap Reduction	Water Conservation
	Short-term	Long-term		
OPTIMIZE ASSET MANAGEMENT		●	●	●
- Optimize inspection frequencies		●	●	
- Optimize repair, rehab, and replacement scheduling		●	●	●
- Optimize service life		●	●	
REDUCE MAIN BREAKS	●	●	●	●
- Reduce contaminant backflow via cross connections	●	●		
- Reduce intrusion from break-induced pressure transients	●	●		
- Reduce contaminant entry at/near main break locations	●	●		
- Reduce water loss			●	●
- Reduce damage costs		●	●	
- Reduce response costs		●	●	
REDUCE LEAKS	●	●	●	●
- Reduce water loss				●
- Reduce failure-inducing conditions at pipe exterior	●	●	●	●

● =the functional benefit cited in row heading benefits the program cited in column heading

Table 7.	**A Conceptual Estimate of Economic Benefits & Acceptable Costs of Main Break Prevention**	
Estimate of potential economic benefits	**Value**	**Units**
Length of installed DW mains in the U.S.†	880,000	Miles
Number of main breaks(N_{MB}) each year in the U.S. †	240,000	Breaks/Yr
Fraction (F1) of N_{MB} that are in high consequence category †	0.01	None
Number of high consequence main breaks/year (N_{HCMB})=F1 (N_{MB}	2400	Breaks/Yr
Average total extra‡ cost(C) of a high consequence main break † ‡ i.e., Total cost above normal main R^3	1,000,000	$
Total Annual Cost of High Consequence MB (C_{HCMB}) = N_{MB} (F1 (C	2.400e+09	$/Yr
Fraction (F2) of N_{HCMB} that are prevented by improved SIM †	0.2	None
Number of prevented high consequence ($N_{P\text{-}HCMB}$) = N_{HCMB} (F2	480	Breaks/Yr
Total Annual Benefit of Inspection (B_{INSP})=N_{HCMB}F1 (F2 (C	**4.80e+08**	**$/Yr**
Estimate of Acceptable Cost of Inspection for High Risk Mains	**Value**	**Units**
Average total extra cost of a high consequence main break (C)†	1,000,000	$/HC break
Average probability of HC main break (P_{HCMB}) is same as average break from (Kirmeyer, 1994) †	0.27	HC breaks/ mi/yr
Annual extra risk from HC main break (C (P_{HCMB})	270,000	$/mi/yr
Annual extra risk from HC main break = Breakeven inspection cost = C_b	270,000	$/mi/yr
Acceptable benefit/cost ratio (R)†	5	None
Acceptable inspection cost/mi/yr for HC main = (C_b/R)	**54,000**	**$/mi/yr**
† Assumptions		

Improved SIM can also, perhaps substantially, reduce premature R^3. If the general condition of U.S. drinking water mains deteriorates due to the pipe replacement rate lagging behind the deterioration rate, there will be an increased need for efficient R^3 decision-making. More efficient R^3 decision-making is supported by accurate and economical pipe condition data. For example, premature abandonment of relatively new prestressed concrete cylinder pipe (PCCP) pipelines has been prevented by the use of new SIM technologies that enable localized, accelerated deterioration of pre-stressing wires to be detected, located, and repaired during scheduled maintenance. Without this capability main breaks would have caused random, frequent, and serious outages that would have made the pipeline too unreliable, hazardous, and costly to continue to operate. As the U.S. distribution system ages and the need to allocate R^3

resources becomes more apparent, there will be an increasing demand for SIM data to support accurate condition assessment and R^3 scheduling.

Looking a bit further into the future, SIM capability improvements now may be laying the groundwork for a revolution in pipe condition assessment models and maintenance practices. Advanced SIM that enables intensive, long-term monitoring of pipeline structural parameters will enable correlations to be sought that will improve applicability and accuracy of service-life models. Advanced SIM that enables frequent and detailed updates of the baseline condition of the pipe should substantially improve the accuracy of service-life predictions by reducing the uncertainty about the actual condition of the pipe at the time the remaining-service-life calculations are made. Advanced SIM technologies that support forecasting of time, location, and modes of failure with greater accuracy will encourage development and implementation of maintenance practices that counteract the early stages of deterioration. This will prevent or delay failures and extend the service life of the pipe network. For example, if coating damage can be promptly and affordably detected and located, this may foster research and development into procedures and equipment to quickly and efficiently repair the problem to prevent more extensive and costly damage to larger areas of pipe, the system, and surroundings. Another major future benefit of improved SIM capability could be early warning about entire classes of pipes/liners/coatings that are deteriorating faster (or slower) than expected. Several years worth of decisions – perhaps at utilities across the country – regarding pipe selection, installation, rehabilitation, or manufacturing practices could be favorably modified as a result of early warning from SIM data. Multiple changes are occurring whose effects on short-term and long-term structural integrity in drinking water systems bear watching via improved SIM, if suitably effective and affordable methods can be devised. These changes include new pipe materials, installation methods, disinfectants, and rehabilitation methods.

Section 4: The Challenges of Improving SIM Capability

In previous sections the shortcomings of existing water main SIM approaches and the benefits of improving SIM capability were described. This section addresses the challenges of improving SIM capability from two perspectives. The first perspective views SIM capability improvement as the process of upgrading the performance and/or cost of the technical sub-tasks that comprise SIM. The second perspective views SIM capability improvement as the process of increasing the value (i.e., the benefits minus the costs) of SIM to the utility.   Subsequent sections will describe new technologies that offer promise for addressing the obstacles to improving SIM performance and cost.

The technical challenge

Meeting the technical challenge of improving SIM capability consists of substantially improving the effectiveness, speed, reliability, or affordability of one or more of the SIM sub-tasks listed in Table 8 for one or more high risk water main situations. A detailed discussion of the challenges involved in improving performance in each of the listed sub-tasks for each high risk main scenario is beyond the scope of the white paper. Inspection of Table 8 reveals that a substantial number of SIM sub-tasks that can potentially be improved, and that a variety of disciplines are required to cause these improvements.

Identifying and measuring pipe flaw parameter(s) with suitable frequency, sensitivity, precision, and accuracy to determine present condition and deterioration rate are difficult challenges. Pipe flaw parameters may include, for example, the location and characteristics (e.g., number, dimensions, magnitude, and location) of leaks, wall thickness, corrosion pits, cracks, pipe cross-section shape, strain, alignment, acoustic and ultrasonic emissions, electrical resistance, electromagnetic field strength, temperature, and various loadings. Pipe flaw parameters must correlate with pipe strength to be useful. Data must exist or be collected to determine the correlation between critical flaw levels and the probability of failure. The flaws must be measurable with sufficient precision to enable differentiation between critical and non-critical flaws.

The fragmentation of application scenarios and research needs is another challenge. Some important examples of fragmentation are listed in Table 9.

Table 8. SIM Generic Sub-task List
● Develop Inspection Plan (What, When, Why, How, Where) ● Specify Critical Flaws or Critical Indicators ● Prepare Pipe for Inspection ● Position the Sensor(s) ● Generate Probe Signal (Active Systems) ● Receive and Store Return Signals and Associated Data ● Partial On-site Analysis ● Transmit Inspection Data to Final Analysis Location ● Analyze Data ● Determine Present Structural Condition of the Pipe ● Determine Deterioration Rate ● Return Pipe to Service ● Repeat above Actions until Inspection Cycle Is Complete ● Provide Power for Preceding Actions ● Maintain the Inspection System Hardware and Software

There are numerous pipe scenarios, and the capability to estimate time and location of failure for one scenario may not be applicable to other pipe scenarios. Multiple SIM approaches are required to address all pipe scenarios, and not all can be developed for and supported by utilities. For a particular pipe scenario (i.e., pipe age/condition/dimensions/material/lining/coating/joints/connections/valves/bedding/external loading/internal loading) there may be a few or many contributing factors that determine when and where a main break will occur. Table 1 lists a number of the factors that may contribute to occurrence of main breaks. Pipe failure scenarios amenable to prediction and prevention via SIM probably need to be moderately simple, or at least need to produce reliable indicators of the onset of failure. A pipe failure that occurs due to multiple and varying causes is likely to be much more unpredictable and may require intensive monitoring (i.e., spatial, temporal, and failure modes) that may be technically and economically infeasible. Another challenge is to determine whether inspection-related technology innovations can effectively and affordably collect useful data for moderate to high risk main break scenarios.

Table 9. Examples of Problem Fragmentation	
Category	**Examples**
Risk	High vs. low consequences Utility vs. customer vs. community Health vs. safety vs. economic Past vs. present vs. future
Pipe material	Metal (CI, DI, S); Concrete (AC, PCCP, Other); Polymer (PVC, HDPE) Lining (Cement mortar, epoxy, polymer pipe); Coating (PE, other)
Failure mode	Corrosion (internal, external, type); loading (seismic, frost, water-pipe temperature gradient, joint loads, surge, beam, point, traffic, combination)
Pipe diameter	Small diameter - higher probability, lower consequences; Large diameter - lower probability, higher consequences
Accessibility	Piggable vs. non-piggable vs. man-entry
Installation status	Past, present, future
Network configurations	Transmission vs. distribution - materials, diameters, number of connections
Size	Large vs. medium vs. small system, budget
Surroundings	Ultra-urban vs. urban vs. rural
Inspection approaches	Inspection parameters & frequency; sensor type & density; data analysis
Research strategies	Incremental improvements to performance & cost of various types of existing technology vs. "leapfrog" technologies that are novel, high-benefit, & high risk.

The variables cited above can pose difficulties for transferring inspection technologies from well-established, high-risk industries. For example: "A wide range of in-line nondestructive evaluation (NDE) methods are used in the oil and gas pipeline industry. Configurations of water distribution piping different from those of oil and gas piping present challenges to extending the use of in-line NDE methods from the oil and gas industry to water pipelines. The inner surface of a water pipe is strongly irregular as a result of scaling, pitting, graphitization, or tuberculation. Aggressive cleaning to provide a clean, smooth inner surface is required for maximum effectiveness with most in-line NDE methods. Oil and gas pipelines typically have long uninterrupted runs of pipe, whereas water piping networks have many bends and connections. These appurtenances produce signals that increase the difficulty of using in-line NDE methods in a water distribution network. Steel pipe, widely used in oil pipelines, is a uniform alloy, whereas CI (cast iron) and DI (ductile iron), common in water pipe networks, are heterogeneous materials. Concrete pipe is both heterogeneous and does not conduct electricity. Both heterogeneity and insulating properties of a pipe wall increase difficulty of applying in-line NDE." (Smith et al., 2000).

The process of taking a SIM technology improvement from invention through successful commercialization is challenging because it is technically difficult, tedious, iterative, risky, and expensive.

The value challenge

A successful SIM technology is one that adds value (V) over its lifetime to utility operations. The general challenges, as well as some of the options for achieving positive value from inspection, are discussed below with reference to equations and insights provided in or derived from "Economic assessment of inspection - the inspection value method" (Wall and Wedgwood, 1998). The equations below concisely identify the factors and interactions affecting inspection value, and the general options for inspection improvement.

The value of inspection is the difference between the benefits (B) and the costs (C) of inspection. Ideally, a SIM technology will be selected when its value exceeds a critical minimum value (Vc) that is greater than zero. Vc is affected by a number of factors: benefits, costs, and value of competing SIM approaches.

$$V = B\text{-}C > Vc > 0 \qquad \text{(Eq. 1)}$$

B is the reduction of the risk of failure, which can be expressed as the product of reduction in the probability of failure ( ) P) times the consequences of failure (CF), in monetary terms if possible. Hence,

$$V = \;)P\;(\;CF - C \qquad \text{(Eq. 2)}$$

Finally, the term)P is itself the product of two terms. "For a single mode of failure of a single component, a suitable inspection would reduce the risk by the factor's POD, the probability of detection, and F, the coverage." (Wall and Wedgwood, 1998).

$$V = POD\;(\;F\;(\;CF\text{-}C \qquad \text{(Eq. 3)}$$

From Equation 1 it can be seen that improving V depends not just on increasing B, but also on controlling C, so that any gains in B are not completely eroded or surpassed by increases in C.

Equation 2 shows the importance of CF on V. The value of CF is the maximum possible value of inspection, and CF is independent of the inspection method. A fundamental challenge of SIM for water mains is the low value and safety of water compared to gas, oil, or other hazardous liquids and gases. Determining CF requires an understanding, the more quantitative the better, of the effects of failure on the utility, its customers, and the surroundings. As CF increases, the potential benefits from inspection increase. Strategies for increasing CF to help achieve V>Vc include: (1) focus inspection resources on high CF situations where there is a reasonable probability of detecting critical flaws; (2) place a high priority on identifying and closely examining high CF situations when setting SIM research priorities; (3) when appropriate, use total and life cycle cost estimation methods, rather than just repair costs, to estimate CF; and

(4) factor relevant cost trends (e.g., water, property values, infrastructure values, labor, demographics, energy) into CF estimates.

Equation 2 also shows the importance of)P, the reduction in the probability of failure, on the magnitude of B, and hence V. The magnitude of)P, which ranges from 0 to 1, determines the fraction of CF that contributes to B. The magnitude of)P is strongly influenced by the performance of the SIM technology. For a given pipe material-critical flaw combination, as an inspection method improves, the number of critical flaws discovered and failures prevented increases. As the magnitude of)P increases, so does B. This is a concise conceptual justification for improving inspection technology.)P, and hence B and V, are also influenced by the condition of the pipe. For example, if the pipe is in poor condition (i.e., high probability of failure), then there is a higher probability of detecting critical flaws and thus achieving a large)P than if the pipe had no or very few flaws. The strategies for increasing the magnitude of)P are to match the SIM technology to pipe conditions to which it is well suited, and to improve the performance of SIM technology as described in more detail in later parts of this section and following sections.

Although in Equation 2 the term)P (CF, the benefit of inspection, is typically considered to be the product of two negatives (i.e., a decrease in the probability of failure times a monetized loss due to the failure), one can also think of the benefit of inspection in terms of the product of an increase in a positive consequence. For example, an increase in the probability of successfully justifying a needed rate increase or obtaining a loan. Also, the failure need not necessarily be a main break and its consequences. The failure could also be a decision-making error that leads to premature R^3.

POD is the ratio of critical flaws detected and those actually present in a representative pipe sample. From Equations 2 and 3, POD has an important influence on)P, and hence on B and V. POD is a function of the behavior of the pipe-loading system, the level of understanding of the pipe-loading system, and inspection device performance. The ability to specify critical flaws requires that the pipe-loading system behaves so that pipe deterioration produces flaws or indicators (e.g., general wall thinning, pits, cracks, bending, change in shape, or acoustic emissions) that are known to correlate to the loss of strength of the pipe and also to the imminent approach of failure, i.e., when loading exceeds strength. The pipe-loading system behavior must be sufficiently understood so that the characteristics of critical flaws (or critical flaw indicators) can be defined. The sensitivity, accuracy, precision, and reliability of the SIM technology influences POD of critical flaws during inspection. The simplest situation for successful inspection is when a predominant, well-characterized type of critical flaw exists, and the inspection method is very effective and reliable in detecting and locating the critical flaw. Strategies for improving POD include: (1) improving and/or verifying the sensitivity, precision, and accuracy of sensing devices for detection and characterization of various types of critical flaws and indicators; (2) increasing the spatial and temporal density of sensors as they become smaller, less costly, more efficient, and more durable, and (3) characterizing material properties, deterioration, flaw initiation and propagation, and failure conditions for inadequately understood pipe-loading systems.

Coverage (F) is defined (Wall and Wedgwood, 1998) for a particular inspection as the fraction of the pipe that is actually inspected. From Equations 2 and 3, F has an important influence on)P, and hence B and V. Strategies for improving F include developing SIM technologies that can more quickly, efficiently, and effectively detect and characterize critical flaws in a greater range of pipe diameters, materials, and coatings that comprise high-risk drinking water mains. Total coverage maximizes the probability of detecting critical flaws. However, the level of coverage that optimizes the value of inspection may be much less than 100% because of the additional cost and reduced incremental benefits as inspection coverage approaches 100%. For example, Wall and Wedgwood (1998) cite an example in which optimal coverage was estimated at 10%. The definition of coverage can also be broadened to include not only spatial coverage, but also temporal coverage. Temporal coverage is the frequency with which the structural parameter is measured (e.g., continuous monitoring, inspection at regular intervals, or no inspection and responding after failure). Continuous monitoring is important if the monitored parameter is a short-term event (e.g., the acoustic emission from a wire break in a prestressed concrete cylinder pipe). Sufficiently frequent inspection is necessary if deterioration rates are to be determined and used for optimizing inspection and maintenance scheduling.

As indicated in Equation 1, C must be effectively controlled if SIM capability improvements are to provide added value for utilities. There are many potential opportunities for reducing inspection costs through inspection technology improvements. One approach is to reduce the labor hours for inspection. This may include reducing the time required to: prepare the pipe/liner/coating for the inspection device; move the inspection device within range of the pipe flaw; collect and store the structural integrity data; return the pipeline to service; analyze the data; and prepare the report. Another approach to cost reduction is to improve reliability, since false positives incur unnecessary repair, rehabilitation, or replacement costs. Improving durability of the inspection system can also reduce costs. Sharing inspection costs within and between utilities may also be an option in some cases. For example, some supervisory control and data acquisition (SCADA) system costs for SIM may be shared with hydraulic and water quality monitoring activities. Higher initial costs for more effective and efficient data collection systems must be balanced against the potential for longer-term benefits and cost reductions.

Section 5: Opportunities for SIM Capability Improvement

Overview

A number of important trends and circumstances make this decade (2004-2014) not only a critical, but also an opportunity-filled time to accelerate the improvement and verification of SIM technology and procedures for drinking water conveyance and storage systems. The feasibility of improving SIM capability for drinking water mains by adapting new technologies has already been demonstrated for a number of situations. Multiple additional needs for SIM improvement have been identified. Advances in relevant science and technology areas, such as sensors, communications, computing, and materials science are occurring that can significantly improve the quantity, quality, timeliness and cost of structural parameter data for determining structural strength, deterioration rates, loading, and approach to failure conditions for various structures. Improvement of SIM technology is typically a lengthy, difficult, costly, and uncertain process. Nonetheless, for various high-risk, non-drinking water applications, multiple SIM improvement attempts are underway. Products (e.g., concepts, prototypes, data, and demonstrations) from these attempts can provide opportunities to economically accelerate the improvement of SIM capability for water mains. Projects are also underway to improve SIM for drinking water mains, but numerous unmet needs still exist. Promising opportunities for productive intra-EPA, interagency, and federal-private collaboration exist. For example, the federal government already possesses substantial research, development, testing, and verification capability relevant to non-destructive evaluation (NDE). EPA can help focus existing Federal capabilities on improvement of drinking water structural integrity monitoring research needs, as the U.S. Department of Energy (DOE) and the U.S. Department of Transportation (DOT) have done for energy pipeline SIM capability improvements. While collaboration will help accelerate and expand the number of options investigated, there is also a need for ranking, in cooperation with the user community and others, the value of potential SIM improvements. This ranking effort will help focus future collaboration efforts.

Opportunities to improve SIM capability

Although improving SIM technology for underground pipelines is difficult, it is possible. This has recently been effectively demonstrated by several technologies for limited sets of drinking water main conditions. For example, Table 10 lists six technologies (i.e., acoustic emission, electromagnetic, impact echo, remote field eddy current (RFEC), seismic, and ultrasonic) and describes the pipe materials and defect types to which they are applicable. Another example of SIM technology improvement is the development

Table 10. Summary of NDE-method Issues that Affect Technique Selection for Various Water Pipe Materials (Dingus et al., 2002)

Inspection method	Pipe material	Defect types	Notes
Acoustic emission	Pretensioned or prestressed concrete pipe	Breaks in reinforcing steel Slippage of broken reinforcement Concrete cracking	Pipe not removed from service Hydrophones left in place for several days to weeks
Electromagnetic	All metallic pipe	Cracks	Commercial, off-the-shelf availability Detect environmental conditions that are likely to weaken pipe Does not directly inspect pipe Totally noninvasive
Impact echo	Concrete pipe containing steel	Delaminations and cracks at various concrete/mortar/steel interfaces	Requires dewatering and human access to interior of pipe Can be done externally if exterior access available
RFEC (Remote Field Eddy Current)	All metallic pipe	Changes in metal mass, graphitization Wall thinning Gouges Large cracks	Commercial, off-the-shelf availability Pig travels through pipe via water hydrants May require cleaning before inspection Pig may dislodge material from pipe wall, requiring flushing
Seismic	All concrete pipe	Reductions in concrete modulus because of aging Reductions in concrete compression as a result of breakage or slippage of reinforcing steel	Requires dewatering and human access to interior pipe
Ultrasonic	All metallic pipe	Detection of wall thinning	Not commercially available for water pipe Does not require dewatering of pipes Developed for inspecting oil or gas pipelines— systems are long, inflexible, and expensive

of instrumented cathodic protection. Cathodic protection for electrically continuous metallic pipes is not a new technique, and is required for gas and petroleum pipelines (Lawrence, 2001). It basically involves sensing and maintaining an electrical potential balance in the system that inhibits corrosion. Instrumented cathodic protection is an improvement that enables the cathodic protection system itself to be monitored, which prevents failures due to malfunctioning cathodic protection systems (e.g., Hock, et al., 1994; Van Blaricum, 1998).

While improvements to SIM technology have occurred, numerous unmet SIM capability improvement needs remain that will require research, development, testing, and verification. As noted in a previous section, existing SIM technologies have many known performance and cost deficiencies. Table 11 lists key SIM technology improvement research needs that were identified in several recent studies on water main inspection technologies.

At least four SIM approaches for water mains appear to the author to have the potential for significant improvement through the incorporation of better and more economical technologies for sensor positioning, sensing, and data storage, transmission, and analysis. These four SIM approaches are: mobile in-line inspection systems; mobile non-intrusive inspection systems, continuous inspection devices, and intelligent systems. These SIM approaches are described immediately below, followed by Table 12, which lists the types of improvements that would enhance their performance and/or affordability.

- **Mobile In-line Inspection (MILI) systems** – These systems require the measuring device to be physically inserted into, moved through, and removed from the pipe. The MILI sensors are usually in close contact with the pipe wall and measure structural parameters over short distances. MILI systems collect structural data for a given area or volume of the pipe for the short interval during each inspection cycle that the sensor is in measuring range of the parameter(s) of interest. Examples of MILI device output are: (1) visual images of the inner surface indexed to pipe location, (2) continuous or discrete wall thickness profiles indexed to pipe location, and (3) void spaces outside the pipe indexed to pipe location. The pipe may have to be drained and/or cleaned to enable MILI devices can be employed. For small diameter pipes MILI devices may be operated either automatically or remotely. For large diameter pipes there is the additional option of direct inspection or MILI device operation by a person.

- **Mobile Non-Intrusive Inspection (MNII) systems** - These systems differ from MILI systems because (1) the detector is not placed inside the pipe. MNII systems that can examine a substantial length of pipe from a single location, preferably without excavation, offer the promise of substantially reducing the time, cost, and disruption involved in pinpointing pipe that should receive detailed scrutiny. Examples include: (1) Lamb wave devices that transmit and receive ultrasonic waves for moderate distances (e.g.,100 ft) along the pipe wall,

Table 11. Selected SIM Research Needs for Drinking Water Mains	**Ref.***
Improved Problem Characterization - Further study of failure mechanisms in water main pipe materials should be conducted. This is necessary to ensure that developing NDT technologies are directed at detecting all defects that are problematic for water mains.	J, M&K
Improvement of Sensing and Reporting - General	
"The recent emergence of some water utility NDE (nondestructive evaluation) hardware is encouraging for the industry, but its application is limited by pipe size, types of materials, and similar issues. These limits typically leave the water utility with more than 90 percent of its system being ineligible for NDE inspection."	D
"Sensor research is needed in the following areas: development of more accurate and precise sensors; development of sensors that can be calibrated remotely; and analysis of the payback time for investments in implementing remote, real-time monitoring using data logging devices and remote telemetry..."	S
Metallic Pipes (Cast and Ductile Irons, Steel, and Mortar and Polymer Lined Metals)	
"... water utility managers are most concerned about ... unlined cast iron and steel piping. Methods for testing and assessing the condition and serviceability of such pipes are expensive and time-consuming, and disruptive to customers. Better approaches to assessment, preferably nondestructive methods for testing, are needed to help utilities define the condition, estimate the future pipe life, and focus their rehabilitation and replacement needs where they are needed most."	K
"Off-the-shelf methods are readily available... Equipment and services are available off the shelf for small-diameter (up to 24 in.) piping. There are, however, areas of research that would increase the confidence that utilities have in these inspections while providing more benefit than currently available from in-service inspections."	D
"Further research needs to be done to develop both ultrasonic inspection and the remote field effect as tools for measuring three-dimensional sizes of corrosion pits."	R
Concrete Pipes	
"To make AE systems (for monitoring wire breaks in PCCP) easier for water utilities to use, it would be best to be able to insert hydrophones through blow-off valves. To accomplish this, manufacturers need to reduce the size of hydrophones. This would help the utilities by causing less interruption to the pipeline and the customers."	D
"Systems for IE (impact-echo), sonic, and AE (acoustic emissions) testing of buried concrete water pipes are commercially available, but ...need further development to correlate NDE results to reductions in pipe integrity..."	D
"There has been essentially no work done on the inspection of A-C (Asbestos-Cement) pipes. ...The applicability of various concrete/cement/mortar NDE methods should be evaluated for ...in situ inspection of A-C water pipes..."	D
* **See end of Table for reference key; Table 11 is continued on next page**	

Table 11. Continued	
Polymer Pipes - "There has been no work done for NDE of polymeric water pipes (i.e., FRP, PE, PVC, and biaxially oriented PVC types ...) Basic (r&d) should be performed to understand failure and defect types. Existing polymer NDE methods should be combined with existing water pipe inspection pig equipment."	D
Improved Coverage by In-line Inspection Devices	
"New pig designs that are specific to the water utility application are needed, and NDE technologies need to be optimized to water pipe materials and their deterioration characteristics."	D
"Because of bends and elbows in water pipes, pig manufacturers need to create fully articulating systems that can get around any corner. The most promising solution for this comes from NDE of boiler tubes that have multiple 180° bends."	D
"Widespread use of piggable (i.e., fully opening) valves would greatly assist in allowing NDE (non-destructive evaluation) tests. Most valves in water systems are not fully opening and do not allow a pig to pass... An impact study could determine if the impacts of switching to fully opening valves would outweigh the benefits of NDE via pigs."	D
Strain Monitoring - Interest was expressed in SIM technology for excessive strain in the pipeline, since some pipe failures occurred from pipes breaking due to bending caused by improper bedding or wash-out of bedding by adjacent leaks.	M&J
D = Dingus et al., 2002; J = Jackson et al., 1992; K = Kirmeyer et al., 1992; M&J= Meegoda and Juliano, 2003 (draft); M&K = Makar and Kleiner, 2000; R = Rajani, et al., 2000; S = Smith et al., 2000	

which enables 200 ft of pipe to be inspected from one location; (2) electric field monitoring devices, which temporarily electrify the pipe, then detect electric field changes at the ground surface that are indicative of pipe wall thinning and indicates problem locations for detailed investigation; and, (3) aerial or satellite systems for remote monitoring of surface conditions indicative of pipe deterioration or failure. Like the MILI systems above, MNII systems provide a "snapshot" of the measured pipe structural parameter(s) during each mobilization/inspection/demobilization cycle.

- **Continuous inspection devices** - These devices collect structural data frequently, which improves the capability for detecting and tracking transient deterioration indicators (e.g., acoustic emissions from cracking, leakage, or wire breaks in prestressed concrete cylinder pipe). These devices can be intrusive (i.e., require placement inside the pipe) or non-intrusive. These devices may be

Table 12. Research Issues for Improving Four SIM Approaches

Performance Improvements	Mobile In-Line Inspection	Mobile, Non-Intrusive Inspection	Continuous Inspection Devices	Intelligent Systems
Improve probability of detection (POD) * Increase parameter measurement sensitivity, precision, accuracy, and speed	●	●	●	●
* Establish correlations between measurable structural integrity indicators, load-bearing capacity, deterioration rates, and failure	●	●	●	●
Improve Coverage (F) * Temporal (sampling rate, duration, reliability)	●	●	●	●
* Spatial coverage (i.e., inspectable volume)	●	●	●	●
* Failure mode coverage (e.g., more flaw types, sizes, alignments, and shapes)	●	●	●	●
* Pipe scenario coverage, e.g.,: - pipe diameters, materials, thicknesses, - pipe, liner, and/or coatings - existing, replacement, rehabilitated, new	●	●	●	●
C Launching and retrieval procedures	●	---	●	---
Improve data screening capability	●	●	●	●
Improve data transmission rates	●	●	●	●
Energy supply strategies & technologies	●	●	●	●
Cost improvements C Identify cost reduction targets for promising advanced SIM system based on benefit-cost analyses: - life-cycle benefit/cost analyses - total benefit/cost analyses	●	●	●	●
C **Reduce equipment, energy, operating & maintenance costs**	●	●	●	●
C **Remote, automatic, continuous-capable operation**	---	●	●	●

● = the type of performance improvement in the row heading would benefit the corresponding class of SIM technology
--- = the type of performance improvement in the row heading would provide minimal benefit

operated on a moderate to long-term basis (i.e., data collection for the inspected area may occur for a day, week, month, or years). The defect to sensor distance may be moderate to long. Cable-mounted hydrophones for acoustic emission monitoring of wire breaks in prestressed concrete cylinder pipes (PCCP) is a continuous inspection device.

- **Intelligent systems** - These are permanent, comprehensive, and automated SIM systems. The sensing and data storage/transmission/analysis capabilities are built-in or retrofitted to the monitored portion of mains. The sensing capability is selected and installed for the desired spatial, temporal, and failure mode coverage. Examples include instrumented cathodic protection (ICP) (e.g., EUPECRMS, 2003), which monitors coating integrity over long distances for cathodically protected pipelines or electrically conductive composite pipe (ECCP), which is a prototype pipe with an embedded sensing layer (Meegoda and Juliano, 2003). Intelligent systems offer the potential for convenient, flexible, rapid, comprehensive, non-disruptive inspection, if they can provide the quality of data needed at an affordable price.

Table 13 lists several potentially preventable classes of main breaks. These types of main breaks are potential target applications for SIM capability improvements.

Table 13. Examples of Potentially Preventable Types of Main Breaks
Cold weather main breaks whose occurrence in typical winter conditions can be accurately forecast in the previous summer based on physical condition data
Main breaks that are preceded by: ● Leaks that cause gradual bedding erosion and detectable excess strain ● Gradual soil movement and excess strain ● Increasing leak rate ● Gradual wall thinning ● Pitting ● Gradual wall deformation ● Mis-alignment ● Acoustic emissions from wire breaks, cracks, and leaks ● Coating failure that changes pipe electrical properties ● Cathodic protection partial or total failure

A number of projects have been undertaken in recent years to improve SIM capability for drinking water mains and other purposes. These efforts should be built upon, not duplicated. A substantial amount of infrastructure SIM research has been completed or is underway for non-water infrastructure purposes that may be transferable to drinking water distribution systems. Much of the other research and development has been directed toward other types of infrastructure (e.g., highways; bridges; tunnels; petroleum, gas, chemical conveyance and storage; nuclear facilities; industrial piping) or other applications (e.g., aviation, military, medical, automotive). Although these applications are often for markedly different physical, chemical, pressure, temperature, flow rate, and economic regimes, there should be some opportunities for transfer of whole technologies, components, procedures, or data to water main applications. Appendices 2.1 through 2.4 provide examples of research sponsored or conducted by various organizations. Appendix 2.1 identifies ten recent or ongoing research efforts to improve SIM technology for drinking water mains. Appendix 2.2 identifies 20 projects to improve SIM capability or the use of SIM data for other types of pipeline applications. Appendix 2.3 identifies non-pipeline research potentially relevant to drinking water SIM applications. Appendix 2.4 is a list of smart/intelligent devices and systems that may be applicable for various SIM applications.

There are many opportunities to interact with other federal agencies to accelerate the evaluation and transfer of new technology for non-water pipeline applications to water main SIM applications. Many Federal agencies are conducting SIM research or have SIM research capability. However, their focus is usually not water pipeline applications, but rather natural gas or hazardous chemical pipelines, other structures, or other applications. Within EPA's Office of Research and Development (ORD), the National Risk Management Research Laboratories' (NRMRL) Water Supply and Water Resources Division (WSWRD) is responsible for distribution systems research. An important role for WSWRD can be to educate other agencies about research needs and priorities for water mains SIM research. EPA can also pursue collaboration on relevant SIM projects where common ground exists between EPA's water-related SIM interests and the other agencies' non-water SIM interests. EPA and the U.S. Department of Defense (DOD) recently completed one interagency agreement on intelligent systems for conveyance and storage systems. Opportunities for follow-up collaboration exist on related projects and programs with DOD (e.g., smart materials and pipelines), DOE (e.g., smart pipes, Intellipipe™, and smart cities), the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce (DOC) (e.g., smart layer technologies), and DOT (e.g., intelligent pipelines for system reliability). The DOE's Strategic Center for Natural Gas and Oil (SCNGO) and the DOT's Office of Pipeline Safety (OPS), have leading roles in promoting, funding, and performing short-term and long-term SIM research, development, and demonstration projects for gas and hazardous liquid pipelines. Between DOE and DOT there are over 40 active structural integrity management technology projects. DOE's FY-03 budget for gas pipeline integrity research is about $7 million. The National Science Foundation (NSF) is a major supporter of research to improve sensors for civil and other systems. Other federal agencies, such as DOD, NIST, and the National Aeronautics and Space Administration (NASA), are also funding or performing multiple research projects that are directly or indirectly applicable to improving structural integrity monitoring for pipelines or other structures. The U.S. Bureau of Reclamation (USBR) previously supported research on a subsequently commercialized system for acoustic monitoring of structural integrity of prestressing wires in prestressed concrete cylinder pipe (PCCP). Seven examples of potential opportunities for SIM research collaboration between EPA and other Federal Agency are identified in Appendix 3.

Complementing non-federal SIM technology research is another route for ORD/NRMRL/WSWRD to accelerate the evaluation or development of improved water main SIM technology. For example, current SIM technology performance is not close to meeting drinking water user community needs, but consensus cost and performance requirements for next-generation SIM technology have not been generated. Inadequately defined cost and performance targets hinder the process of generating interest and support for research to address the problem. ORD/NRMRL/WSWRD can cooperate with the user community (e.g., AwwaRF, individual utilities) to define these requirements by expert workshop and/or survey. The expectation is that once the target performance and cost requirements are defined, it will become clear that: (1) achieving next-generation SIM requirements will require research activity that covers the full range of possibilities from fundamental research to verification of commercialized SIM technologies, (2) private sector research resources alone cannot address all high priority SIM approaches and pipe scenarios in an expeditious manner, and (3) ORD/NRMRL/WSWRD and other federal research resources (e.g., personnel, facilities, funding) can be invaluable for significantly accelerating the completion of SIM improvement research. Based on the consensus cost and performance targets, ORD/NRMRL/WSWRD can conduct complementary research and can also promote within the federal research sector the inclusion of next-generation SIM needs in federal research, development, demonstration or verification activities.

ORD/NRMRL/WSWRD can also work with non-federal organizations to investigate high-benefit technologies that are typically too high-risk for user community and other non-federal research programs. AwwaRF and specific utilities with active research programs are key user community research organizations, and their research focuses directly on water main applications. AwwaRF receives federal funding (e.g., $4.8 million in FY-04 from EPA) for research, but only a portion of these funds are applied to AwwaRF's infrastructure reliability (IR) program, and only a portion of the IR program addresses SIM evaluation or improvement. Given the range of unmet research needs, AwwaRF research support alone is insufficient to address SIM capability improvement. Foreign research efforts in water main inspection and condition assessment, particularly in Europe, Canada, and Australia offer collaboration opportunities. The Water Environment Research Foundation (WERF) is another potential collaborator to the extent that common ground can be found between SIM research needs for wastewater mains and drinking water mains. AwwaRF, WERF, and EPA are currently cooperating to issue an RFP (Protocols for Assessing Condition and Performance of Water and Wastewater Assets, WERF Request for Proposals No. 03-CTS-20CO). Other relevant research entities include the private sector (e.g., inspection device manufacturers and service providers), academia, private research organizations, non-profit research organizations, and various partnerships and consortia that are producing and evaluating components or systems potentially relevant to drinking water mains SIM.

EPA/ORD already has several programs that can potentially support SIM research for water mains, but so far these programs have not been applied in a coordinated manner for that purpose. The ORD programs that are the prime candidates for collaborative efforts include ORD/NRMRL/WSWRD distribution system research program and the Environmental Technology Verification (ETV) program; the National Center for Environmental Research's (NCER) Small Business Innovation Research (SBIR) program; the National Homeland Security Research Center (NHSRC), and the Office of Science Policy's Federal Laboratory Consortium (FLC) project. Table 14 summarizes the capabilities of these programs with regard to SIM improvement research. If performance and cost improvement targets are defined for next-generation SIM technologies, then this will provide a strong basis for increased intra-ORD collaboration to help meet critical targets.

Table 14. Opportunities for Intra-EPA/ORD Research Collaboration

EPA/ORD Organization	SIM Collaboration Opportunities
NRMRL/WSWRD	The NRMRL/WSWRD research program has the following SIM research potential: - in-house, extramural contract, & interagency research program - a pipeline test apparatus (2" to 12", 500 to 1000-ft, buried, steel) in Edison, NJ - water quality monitoring, modeling, and control expertise - distribution system simulator in Cincinnati, OH - a project with AwwaRF to define next-generation SIM performance and cost targets - potential for field-scale, controlled condition tests of leak detection devices, smart pigs, and other condition assessment tools
NRMRL/ETV	The ETV program verifies performance claims for commercially available technology; water infrastructure monitoring technology could potentially be within scope; verifications could potentially utilize NRMRL/WSWRD test facilities.
NHSRC	NHSRC is a potential collaborator with NRMRL for research to address SIM needs that overlap water security needs. Potential overlaps include: 3rd party detection to prevent construction strikes and 3rd party detection to protect against terrorist intrusion; surveillance systems; sensors; data transmission, storage, & analysis; and post-failure/disaster inspection & assessment methods.
NCER/SBIR	SBIR involves prototype development and evaluation, and offers opportunities to focus small business research on SIM research for water mains.
OSP/FLC	OSP represents EPA on FLC. The FLC mission is -- "To promote and facilitate the rapid movement of federal laboratory research results and technologies into the mainstream of the U.S. economy." May provide useful links with other federal agencies.

Section 6: Conclusions and Recommendations

1. **SIM capability improvements will provide multiple public benefits, so there are multiple reasons for public agencies to support R,D,T,&V in this area.** Substantial improvements to the state-of-the-art of structural integrity monitoring will yield health, water quality, water conservation, asset management, and economic benefits to water utilities and the public. These benefits will occur over both the short-term and the long-term. The most obvious health-related benefit will be reduction in preventable high risk water main breaks and their associated health risks from loss of pressure, which can cause backflow and intrusion of contaminants, and suspension of contaminated sediments. Reduction in high consequence main breaks also provides a substantial economic benefit from avoided response and damage costs. Another important benefit of improved SIM capability is more optimized R^3 scheduling, which helps to ensure that pipes are used as long as safely possible. Other beneficial spinoffs may occur, such as new preventive maintenance technologies made feasible by more comprehensive, timely, and precise data on pipe deterioration.
2. **Consensus, quantitative benefit, cost, and performance targets for SIM capability improvements would be useful.** The development of better distribution system structural monitoring technologies for water mains can be accelerated by attracting more attention from the federal and non-federal research community. More attention to SIM research needs can be created by generating and publicizing consensus, quantitative performance-, benefit-, and cost-improvement targets for inspection and condition assessment technologies for various critical application scenarios. These targets must be developed in close coordination with the user community and technical experts. This topic is a good candidate for an EPA-AwwaRF collaborative effort.
3. **Advanced structural integrity monitoring technologies and procedures should be developed first for applications where they are most likely to have favorable benefit-cost ratios.** These application scenarios include those where main breaks are expected to produce: high consequence of failure (e.g., major adverse effects on customers, utilities, or communities) and high frequency, moderate consequence failures (e.g., earthquake-prone areas, systems with a substantial amount of deteriorated pipes). Advanced SIM may also be particularly beneficial for monitoring new technologies to provide cost and performance decisions for new technologies that have limited documentation of successful short-term and long-term performance under a range of real conditions (e.g., new pipe materials or configurations, new liner technologies, and new installation technologies). Finally, when very low-cost SIM technologies and components are developed, then previous relevant applications that were dismissed due to cost considerations become candidates for re-evaluation.
4. **Government research support can be critical for addressing fragmented problems whose solution will provide public benefits.** The distribution

system SIM problem and technology market are fragmented into numerous smaller problems and markets for a variety of reasons (e.g., various types of pipe materials, diameters, coatings, linings, configurations, and consequences of failure). Multiple SIM technologies and procedures will require improvement to substantially improve SIM capability on a national scale. Fragmentation reduces the potential return on research investment by the private sector. The federal government has previously played an instrumental role in supporting research that led, for example, to development of acoustic methods for monitoring PCCP deterioration, and for acoustic emission monitoring of leaks.

5. **Vigorous, increased, systematic EPA-ORD and other government support and participation is recommended to ensure that improvements to SIM capability for distribution systems occur in a timely manner.** The "water infrastructure replacement era" has already started. Improved SIM capability for supporting R^3 decision-making will be particularly beneficial during the "replacement era." The sooner SIM technology improvements are applied, the greater will be the benefits. Government-supported acceleration of SIM technology R,D,T&V helps ensure that promising inspection technologies get timely consideration in the marketplace.
6. **Federal R,D,T,&V capabilities should be used to accelerate, and complement the AwwaRF infrastructure reliability research program**.
    a. **ORD/NRMRL/WSWRD should work with AwwaRF to develop SIM cost and performance improvement targets for the various classes of next-generation SIM technology.** EPA should promote R,D,T,&V in relevant, existing EPA and other federal research programs.
    b. **ORD/NRMRL/WSWRD should evaluate the potential for cooperation with AwwaRF in structural integrity monitoring and condition assessment technology evaluations.** Options include the EPA's ETV program, Federal sites of opportunity (e.g., DOD, DOE, or General Services Administration (GSA) sites) or at Federal testing sites (e.g., underground pipeline test apparatus at EPA-Edison, NJ; distribution system simulator at EPA-Cincinnati, OH; or DOE test facilities).
    c. **EPA should promote cooperative research and technology transfer efforts among relevant Federal research organizations to address the long-term drinking water mains structural integrity performance and cost targets identified in consultation with AwwaRF and the user community**. Potential cooperating agencies include DOD, DOE, DOT, NASA, and NSF.
7. **This white paper should be circulated to relevant EPA and other Federal Agencies as a first step to exploring options for improving intra-EPA and intra-Federal coordination regarding SIM capability improvement for drinking water infrastructure research to accelerate production of useful products and data.**

8. **ORD/NRMRL/WSWRD/UWMB should continue to be a champion/sponsor of research on advanced SIM.** Near-term targets should include technical and economic evaluations of intelligent systems for monitoring structural integrity of buried pipe systems, which is receiving increased attention for non–DW piping systems; systems for monitoring strain caused by bedding washout; and perhaps evaluation of leak detection as a method for identifying and prioritizing future main break locations.
9. **ORD/NRMRL/WSWRD/UWMB should evaluate the need for and, as applicable, promote the use of its Pipeline Test Apparatus (PTA) for evaluation of advanced SIM technologies**. The PTA is potentially valuable for controlled-condition evaluations of promising leak detection/location/quantification devices; in-line inspection devices; external inspection devices; remote coating inspection devices; smart/intelligent pipes; and decontamination procedures. A number of improved in-line inspection devices should be produced from a series of ongoing DOT and DOE projects for natural gas pipeline applications. The evaluation of the PTA should include identification of any necessary modifications to support the tests.
10. **Understanding the limitations of SIM capability is important for setting research and user priorities.** It is important to identify and document the technical and cost limitations of SIM and make this information available to decision-makers. For example, if existing and/or feasible monitoring devices cannot measure key structural parameters, or can only measure them with insufficient accuracy or spatial and temporal coverage, it is very useful to document these findings. This will prevent misapplication of research or utility funds to systems or applications where the performance or cost of SIM does not or cannot meet the required levels.

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Appendices

Appendix 1. Examples of Recent High Consequence Main Breaks			
Date	**Location (Main Size)**	**Key Damages**	**Reference**
11/96	Cranston, RI (Unknown)	$2 million emergency repair 15 to 20 Mgal lost	Fortner, 1999
01/98	5th Avenue, New York, NY (Unknown)	Street Collapse Flooding damage Ruptured gas line Business disruption	www.ci.nyc.us/html/dep/html/dep/html/watermain.html
01/00	9500 Rhode Island Ave., College Park, MD (30-in)	House de-stabilized Flooding Road buckled	www.inform.umd.edu/Diamondback/00-01-31/news3.html
03/00	841 to 853 Broadway New York, NY (36-in)	14 businesses damaged 120 businesses ~ 2 weeks	www.state.ny.us/governor/press/year 00/May 9_1_00.htm
02/01	Dallas, TX (84-in)	30 homes affected Initial assessment: $1,000,000 - structure $1,000,000 - contents	www.dallas fire rescue.com/press items/02_08_01_html
02/01	Fountain & Silverwood Phila., PA (30-in)	Sewer damage Upper hospital floors w/o water several hours Pressure loss	www.phila.gov/water/press/releases/index_15.html
03/01	38th St. & Franklin Blvd. Cleveland, OH (30-in)	6 schools closed Low water pressure Boil water advisory Street damage Basement flooding Home de-stabilized > 1 MM gal lost	www.cleveland.com/news/index.ssf?/news/pd/C29flood.html

Appendix 1. Continued			
Date	**Location (Main Size)**	**Key Damages**	**Reference**
07/02	1900 Vickery St. & Interstate 30 Fort Worth, TX (30-in)	Roadway Flooding -2 hydroplane accidents Disruption of service to 2 hospitals, OK on backup systems	www.nbc5i.com/news/1553333/detail.html
10/02	Clay St. & Cullen Blvd. Houston, TX (60-in)	12-block area affected Evacuated homes via boat Home & vehicle damage ================ $900,000 from city to repair and replace homes	www.click2houston.com/news/1718677/detail.html ================ abclocal.go.com/ktrk/news/2063_local_watermain.html
11/02	Chicago, IL (36-in)	Lake Shore Drive closed ~ 2 days Sinkhole 30' w, 9' deep Several cars submerged Basement flooding	www.nbc5.com/news/1774221/detail.html
01/03	18th & 19th St., Brooklyn, NY	N, R and W subway lines disrupted	stacks.msnbc.com/local/wnbc/a1458601.asp
01/03	Pittsfield, MA (unknown)	Tank drained (300,000 gal) Schools & businesses closed Low pressure Service disruption ~1,300 customers Icing	www.pittsfield.org/news_2003/012903 waterb.htm
08/03	9th & Lombard, Phila., PA(8-in)	Flooded electrical service One-day power outage -26,000 homes -businesses; 2 hospitals	kyw.com/news/local_story_224122428.html
09/03	Detroit, MI (48-in)	I-96 shut down Damage to roadway	www.wndu.com/news/092003/news_21656.php

Appendix 2.1 Examples of Current SIM Research for Drinking Water Conveyance Systems

Category	Materials	Year	Title	Sponsor/No. *
Problem Characterization	Multiple	2003	Health effects from distribution systems (meetings, white papers)	EPA-OGWDW
	Multiple	2003	Water distribution system management system... for the planning of rehabilitation integrating statistical failure models	NSF/0118376
	Polymer	2005	Long-term performance prediction for polyvinyl chloride pipe	AwwaRF/2879
Technology R,D,T,&V	Multiple	2003	Workshop on non-interruptive condition assessment inspection devices for water transmission mains	AwwaRF/2871
	Multiple	2003	Techniques for monitoring structural behavior of piping systems	AwwaRF/2612
	Multiple	2003	Non-contact sensors for pipe inspection by Lamb waves	NSF/9901221
	Multiple	2004	Testing, condition assessment of joints in water distribution pipelines	AwwaRF/2689
	Multiple	2004	Pervasive monitoring & control of water lifeline systems for disaster recovery	NSF/0112665
	Polymer	2004	Intelligent systems for conveyance and storage infrastructure	EPA-DOD/ No. 97938349
	Concrete (PCCP)*	2002	SBIR Phase II: Wireless acoustic emission sensor system for quantitative nondestructive evaluation and in situ testing of prestressed concrete cylinder pipe	NSF/9984235 & 9760242

* AwwaRF = American Water Works Association Research Foundation
EPA = U.S. Environmental Protection Agency
DOD = U.S. Department of Defense
NSF = National Science Foundation
OGWDW = Office of Ground Water and Drinking Water, Office of Water, EPA
PCCP = prestressed concrete cylinder pipe
R,D,T,&V = Research, development, testing, & verification

Appendix 2.2 Current/Recent SIM Research for Non-Drinking Water Pipelines that is Potentially Applicable to Drinking Water Conveyance Systems				
Category	**Materials**	**Year**	**Title**	**Sponsor/No.**
Problem Characterization	Multiple	—	Fitness-for-service models and procedures for metals, concrete/ cement, polymers, and composites (Examples below)	
	* Polymer	1999	* PE Lifespan Forecasting: Plastic Piping Systems	Gas Technology Institute/(98/0358)
	* Multiple	2000	* Recommended Practice for Fitness for Service (API RP 579)	American Petroleum Institute
	* Metal (Steel)	1991	* Manual for Determining the Remaining Strength of Corroded Pipelines (ASME B31G-1991)	American Society of Mechanical Engineers
	* Multiple	-----	* MANTOP - maintenance management scheduling based on probability of failures and cost of consequences	Southwest Research Institute
	*Concrete	-----	Various models for predicting the deterioration of concrete structures (e.g., bridge decks exposed to road salts)	Multiple
Technology R,D,T,&V	Multiple	2002	User Costs in Seismic Risk Management for Urban Infrastructure Systems	NSF/9802151
	Multiple	2003	Intellipipe™ - system for high speed data transmission from sub-surface drill bit to surface	DOE-Industry Partnership
	Multiple	2004	Digital mapping of buried pipelines with a dual array system http://primis.rspa.dot.gov/matrix/	U.S. DOT/ DTRS56-02-T-0005
	Multiple	2005	Intelligent systems for pipeline infrastructure systems for pipeline infrastructure reliability http://primis.rspa.dot.gov/matrix/	NRC-Canada/ U.S. DOT/U.S. DOI DTRS56-00-X-0035
	Metal	2005 (start)	Improved material performance and other pipeline safety improvements	U.S. DOT/ DTRS56 -04-BAA-0002

Appendix 2.2 Continued

Category	Materials	Year	Title	Sponsor/No.
Technology R,D,T,&V	Metal	2003	Baseline study of alternative in-line inspection vehicles	U.S. DOT DTRS56-02-T-0004
	Metal	2004	In-line stress measurement by continuous Barkhausen method	U.S. DOT DTRS56-02-T-0003
	Metal	2004	Mechanical damage inspection by magnetic flux leakage (MFL)	U.S. DOT DTRS56-02-T-0002
	Metal	2004	Enhancement of the long-range ultrasonic method for the detection of degradation in buried, unpiggable pipelines	U.S. DOT DTRS56-02-T-0007
	Metal	2004	NoPig metal-loss detection system for non-piggable pipelines	U.S. DOT DTRS56-03-T-0006
	Metal	2003	Advanced passive-acoustic leak location and detection verification system for underground fuel pipelines	DOD-ESTCP CP-9904
	Metal	2004	Fiber optic sensor suite for corrosion and flow-assurance monitoring in deepwater flowlines	NIST/ATP 00-00-4611
	Plastic	2004	Pipeline damage prevention --locatable magnetic plastic pipe	U.S. DOT DTRS56-02-T-0006
	Plastic	2006	Framework for integrating embedded sensors in durability analysis of FRP composites in civil infrastructure	NSF/0093678

Appendix 2.3 Research for Non-pipeline Applications Relevant to SIM Improvement				
Category	**Materials**	**Year**	**Title**	**Sponsor/No.**
Technology R,D,T,&V	Multiple (Mult)	Indef	Federal Government NDT/NDE capability - personnel, facilities, funds, and programs potentially applicable to water infrastructure R,D,T,&V. For example, DOD Nondestructive Testing Information Analysis Center (NTIAC); WSWRD/EPA, DOE, and DOD have pipeline test apparatus.	DOE; DOD; EPA; DOT; NASA; NIST, etc.
	Mult	Mult	"Smart" or "intelligent" technologies from material-scale to city-scale – SEE SMART/INTELLIGENT TECHNOLOGIES TABLE	Mult
	Mult	2004	Structural health monitoring via SMART layer™	NIST/ATP 00-00-4404
	Mult	2004	Sensors and sensor networks	NSF/04-522
	Mult	2003	Intelligent naval sensors - grand challenge research program – sensors that are 10X smaller; 100X faster; use 0.001X energy	Office of Naval Research
	Mult	2007	Center for Embedded Network Systems –embedded network sensing systems; small, energy scavenging sensor systems - http://cens.ucla.edu/default/htm	NSF/ 0120778
	Mult	Indef	Center for Infrastructure Technology Research in the Interest of Society- energy scavenging sensors, smart buildings - http://www.citris.berkeley.edu/program	UC Berkeley
	Mult	Indef	Facility Environmental Monitoring and Management Systems Program - improving monitoring technology for ... water ... at arsenals	DOD/ Industrial Ecol. Center
	Mult	Mult	Structural integrity monitoring for bridges (e.g., http://www.di3.drexel.edu)	Mult
	Mult	On-going	Sewers as fiber optic cable conduit- http://www.citynettelecom.com/	Citynet Corp.
	Mult	On-going	Use of electric powerlines for transmitting data - http://www.ambientcorp.com; http://www.echelon.com/products/oem/transceivers/powerline/default.htm	Mult

Appendix 2.4 Examples of Smart/Intelligent Devices & Systems
Smart dust - small integrated sensing & data storage, analysis, &/or transmission devices.
Smart pebbles - U.S. DOT project to develop/test low-cost, stay-in-place, queriable sensors to monitor chloride content from road salt in concrete bridge decks.
Smart bricks - bricks or other structural component outfitted with smart dust-type devices to measure and report motion, vibration, etc.
Smart bolt - U.S. Air Force - deformation of wing anchor bolts made of TRIP (transformation induced plasticity) steel can be monitored for deformation state without disassembly, reduces inspection time and cost.
Smart nose - smart sensor for analysis of vapors, may be relevant structural monitoring if volatile compounds indicate deterioration.
Smart tongue - smart sensor for analysis of compounds in water, may be relevant for structural monitoring if dissolved compounds indicate deterioration.
Smart pigs - several organizations (e.g., AwwaRF, DOT, DOE, & private sector are conducting research on in-line pipe inspection devices with sensors to detect and record a variety of structural parameters.
Smart pipe - incorporation of sensing capability into pipe. Sensors may monitor fluid, pipe, or loading parameters; sensor location and spacing may vary widely.
Smart structures and buildings – buildings equipped with sensors (e.g., vibration, orientation, motion, and strain) in key locations that enable rapid assessment of structural stability. Reductions in cost of sensor increase economic feasibility of denser sensor arrays.
Intelligent systems – integration of sensing, data storage, remote data analysis, data transmission, detailed central analysis, condition assessment to support proactive, condition-based maintenance. EPA, DOD, DOT, DOE, and NIST have research projects in this area.

Appendix 3. Examples of Interagency Collaboration Opportunities	
Project Title/Goal/Description:	**Potential Collaborators**
R,D,T,&V of Intelligent Systems for SIM Applications EPA and DOD recently completed one interagency agreement on intelligent systems for conveyance and storage systems. Other opportunities for collaboration exist with DOD (e.g., smart materials, pipelines), DOE (e.g., smart pipes, smart cities), NIST (e.g., smart layer technologies), DOT (e.g., intelligent pipelines for system reliability), and NSF (e.g., sensing and civil and mechanical systems research programs).	EPA, DOD, DOE, NIST, DOT, NSF
Improvement of In-Line and External Inspection Technologies The DOE's Strategic Center for Natural Gas and Oil (SCNGO) in its National Energy Technology Laboratory (NETL) and the DOT's Office of Pipeline Safety (OPS), have leading roles in promoting, funding, and performing structural integrity monitoring research, development, and demonstration projects for gas and hazardous liquid pipelines. Between DOE and DOT there are over 40 active structural integrity management technology projects. DOE's FY-03 budget for gas pipeline integrity research was about $7 million.	EPA, DOE, DOT
Integral Communication, Damage Detection, and Multiple Sensor Applications in Pipelines/DOE Project No.: FWP-4340-70A /http://www.netl.doe.gov/scng/ **Goal (DOE):** The ultimate goal is to obtain real-time information concerning the pipeline infrastructure so that the security of the system can be assured and efficiency of the system can be maximized. **Description (DOE):** In this project, thermal spray was used to deposit fine metallic powders, wire, or even non-metallic materials on sections of pipe. Its ability to be utilized for data transmission or to detect third party damage was evaluated. DOE Phase I - 7/2001 to 9/2002.	EPA & DOE
Title (EPA): Improvement and evaluation of above ground survey technology for buried pipelines **Goal (EPA):** Verification and/or improvement of non-invasive technology for buried metallic pipelines. **Description (EPA):** Possible cooperative project with water utility that has been evaluating a private company's above ground pipeline survey technology. First set of tests by utility on large diameter pipelines identified the pipeline alignment, depth, and picked-up all non- isolated service connections and laterals. Utility is interested in a partnership project to further develop and evaluate the device. Improvements sought include capability to identify soil condition, moisture content, corrosion pitting and other symptoms indicative of severe pipeline degradation.	EPA & DOT &/or DOE &/or NSF

Appendix 3. Continued	
Project Title/Goal/Description:	**Potential Collaborators**
Title (DOT): **NoPig Metal-Loss Detection System for Non-Piggable Pipelines/** DTRS56-03-T-0006 - http://ops.cycla.com/matrix/ **Goal (DOT):** The project goals are to: confirm the NoPig System provides accurate pipeline metal-loss detection within present specifications; improve the system to be able to discriminate between defects; and, apply the technology to larger diameter pipelines for metal-loss detection and discrimination. **Description (DOT):** The NoPig Pipeline Inspection System has been developed as a method for detecting metal loss anomalies on small diameter non-piggable pipelines from above ground. Contact points at two places no farther than 500 meters from each other are needed. The technology makes use of the skin effect. It utilizes a difference between magnetic fields at low and high frequency produced by electric currents passed through the pipe under test. The low frequency current will distribute itself and travel throughout the entire cross section of the pipe. The high frequency current will travel along the outer surface of the pipe (skin effect). Both currents generate a magnetic field which shape is dependent on the presence of a defect. **Project Period:** 07/2003 to 07/2005.	EPA & DOT
Title (DOE): New Acoustic Wave Pipe Inspection System/ DOE Project No.: FEAB201/URL: http://www.netl.doe.gov/scng/ **Goal (DOE):** To demonstrate a new wave guide pipe flaw detection technique that will detect flaws in a single pass. **Description (DOE):** The technical approach is to use an acoustic signal directed through the walls of the pipe and along the length of the pipe. Acoustic receivers utilizing microcantilever sensors will detect reflected, dispersed, and scattered signals to which advanced signal processing methods will be applied to identify such flaws as cracks, corrosion pits, gouges, and leaks. These sensors, receivers, and actuators will be integrated into a compact (4 to 5 inches in diameter by 24-inch long) in-line inspection tool suitable for transmission and distribution pipelines. **Project Period:** 08/2001 to 11/2003.	EPA & DOE
Title (DOE): A Data Fusion System for the Non-Destructive Evaluation of Non-Piggable Pipes /DOE Project No.: DE-FC26-02NT41648/URL: http://www.netl.doe.gov/scng/ **Goal (DOE):**To design sensor data fusion algorithms that can synergistically combine defect-related information from heterogeneous sensors. **Description (DOE):** These sensors are used to inspect natural gas pipelines for reliably and accurately predicting the condition of the pipe-wall. This work will also develop efficient data management techniques for signals obtained during multi-sensor interrogation of a gas pipeline. **Project Period:** 09/2002 to 09/2004; DOE Cooperative Agreement with Rowan University.	EPA & DOE