OBJECTIVE:
The overall objective of this research study was to explore the current conditions and state of the art in management of asbestos cement (AC) water main assets and develop a practical, comprehensive guidance manual to be used by the owners of these assets. Issues to be addressed included pipe deterioration and failure, condition assessment, remaining service life prediction, rehabilitation and replacement, and health and waste management protocols.

BACKGROUND:
AC pipe has been installed in water systems in North America starting in the 1930s and up until the early 1980s, mainly as an affordable, non-corroding alternative to metallic pipes in areas prone to corrosion. Health concerns associated with the mining, installation, removal, and disposal of asbestos products ended the selection and installation of new AC pipe, although there was no evidence of water-born fiber related illnesses. Estimates of the current level of AC pipe inventory still in operation (as of the mid-1990s) in North America were as high as 12 to 15% of all potable water mains.

AC pipes can deteriorate as a result of a variety of factors, including working environment and operational conditions, and eventually, when stresses exceed their strength, they fail. There is a substantial variability in the deterioration rate of AC pipes, and therefore also in their condition. Since total replacement is economically infeasible for many utilities, there is a great need to develop effective renewal strategies.

There has been some work done on this subject in Europe and Australia. However, the applicability of the work to AC pipes in North American water utilities has not been addressed. Furthermore, relatively little information and literature exists on life expectancy and management of North American AC pipes. This study is intended to close this gap.

APPROACH:

Comprehensive literature review and survey. A comprehensive literature review was conducted to summarize the current knowledge on deterioration mechanisms and factors affecting failure of AC pipes, condition assessment techniques, methods to estimate remaining service life, and management practices for AC water mains. This information was used as a basis for a survey of 20 utilities in the United States and Canada on their AC pipe inventory, breakage rates, working environments, and management practices.
The survey data were analyzed to correlate breakage rates with pipe characteristics (e.g., pipe size) and working environments (e.g., water quality, water temperature, burial depth, backfill soil types, and soil pore water pH and sulfate content) and to identify factors that affect the deterioration and eventual failure of AC pipes in North America.

**Condition assessment, modeling, and remaining service life estimation.** AC pipes samples were obtained from 10 participating utilities for inspection and condition assessment of sub-samples (specimens). The condition of AC pipe specimens was assessed by measuring the degradation depth (thickness) of the inner and outer pipe walls and testing residual pipe strength. Assessment techniques, including chemical (phenolphthalein staining tests) and mechanical (Shore D hardness, crush, and pressure) tests, were conducted on AC specimens and evaluated for their capability to measure degradation and assess the residual load-bearing capacity. In addition, scanning electron microscopic analyses were carried out on selected pipe specimens to further understand the nature and extent of deterioration through examination of changes in weight percentage of elements and microstructure.

Pipe degradation depths were correlated with pipe residual strengths, microstructure characteristics, pipe age, water quality, and soil properties to understand possible relationships and develop degradation rate models. These degradation rate models, together with knowledge about the current pipe condition, allow estimation of pipe residual strength over time. Acting loads applicable to AC water mains were identified from relevant standards (e.g., AWWA C401) and from the comprehensive survey. Time to failure can be estimated as the time at which acting loads exceed residual pipe strength.

**Rehabilitation and replacement (R&R) methods and related health and waste management.** The selection of methods for AC pipe R&R needs to consider the potential risk of exposure to asbestos fibers for workers and the general public, and to follow relevant regulations, such as the Asbestos National Emission Standards for Hazardous Air Pollutants (NESHAP) and the Occupational Safety and Health Administration (OSHA) regulations. A set of R&R methods was evaluated for their risk to release asbestos fibers by referring to the asbestos NESHAP and OSHA requirements. From this review, suitable methods were identified for R&R of AC pipes.

Although the recommended R&R methods have the least risk to the workers and the public, some asbestos fibers may still be released. Appropriate measures are also required for the handling and disposal of AC pipe fragments. Current utility and contractor practices were studied, and recommendations for health and waste management practices during R&R activities were developed.

**RESULTS/CONCLUSIONS:**

**AC condition in North America.** Water quality, pipe diameter, and pipe age are identified as factors (with the highest coefficients of determination) that contribute to AC pipe failures. Internal degradation is more severe for conveyed water with low aggressiveness index, soft water, or water with low alkalinity. Soil movement contributes
to failures of small diameter pipes in mid-western and western North America communities with expansive clay soil. Pipe age is a surrogate of many contributing factors, e.g., soils.

Breakage rates of AC pipes in the United States and Canada seem to be substantially lower than breakage rates observed in cast and ductile iron pipes (cast iron and ductile iron pipes account for over 60% of water mains in North America). All but one of the tested pipes are still adequate to bear the external loads and internal pressures that they experience. However, pipe breakage rates varied from utility to utility. For a given utility, they varied yearly, indicating likely differences in pipe properties, working environments, and other conditions.

**Condition assessment, modeling, and remaining service life estimation.** A set of assessment protocols was recommended based on the need for utilities to understand the condition of AC pipes at the utility (or system) level and at the pipe section level. The recommendations included analysis of historical break data, conveyed water quality, and soil pore water quality for a utility, and phenolphthalein staining and strength tests for pipe sections. The residual pipe strengths are clearly related to the depth of degradation obtained from the phenolphthalein staining tests and element analyses, and therefore can be estimated by testing the degradation depths.

A degradation depth model was developed, which is dependent on pipe age, water quality, and soil pore water pH. However, relatively low coefficients of determination in the various regression analyses warrant caution in the application of the results. The uncertainties are likely a result of the rather limited data set upon which they are based, as well as the fact that much of the collected information represented a snapshot in time (e.g., the current conveyed water quality data) rather than an extended history. It is therefore recognized that the proposed models represent only a first step towards accurate estimation of the deterioration depths and rates for AC pipes, and towards having the ability to predict long-term pipe condition.

The expected remaining service life predictions made using data collected on AC pipes from several utilities vary significantly from utility to utility and even within utilities, depending on the water quality and soil environments. AC pipes in some regions were subjected to aggressive water quality and soil environments and their expected remaining lives ranged from imminent failure to 50 years. In regions with less aggressive water quality and dry soil conditions, AC pipes might be expected to serve for another 100 to 150 years. However, active soil movement can cause premature failure of an AC pipe, substantially reducing its expected remaining service life.

**Rehabilitation and replacement methods and related health and waste management.** Repair methods using trenching and trenchless methods like pipe lining, sliplining, cured-in-place lining, and similar methods are the best R&R methods, because asbestos fiber release can be controlled. Pipe bursting, pipe reaming, and pipe eating methods break the pipes into pieces and leave some or all of the AC fragments in the ground, potentially creating a hazardous-waste site. These methods are severely restricted by NESHAP. They
can only be used when the affected length is less than 80 m (260 linear feet). Local authorities may impose even stricter limits on the maximum length for using these R&R methods.

Recommendations are proposed to enable project managers to minimize the risk of exposure of workers and the public to asbestos fibers. They cover good practices on AC pipe projects: for staff training, site security; personal protection, excavation of AC pipes, on-site abandonment, removal from site and transportation of materials to specifically designed sites for appropriate disposal, and monitoring of the disposal sites.

APPLICATIONS/RECOMMENDATIONS:

Research report and guidance manual. A two-tier document was developed to communicate and apply the results of this research. The first tier is a succinct yet comprehensive guidance manual, intended to provide structured assistance to users. In addition to providing instructions on the various issues, the guidance manual will also provide pointers to corresponding issues in this technical report (second tier), for users who are interested in more in-depth technical background.

Recommendations for further study. One of the key components for estimating the remaining service life of AC water mains is degradation rate models. The model developed in this study is based on a small number of samples. It is recommended that a larger number of samples be tested to validate and refine the models, especially including samples from a wider range (and more detailed history) of water quality and soil conditions, and with regard to covering geographic areas not represented by the data from the participating utilities (e.g., utilities from the eastern United States).

It is also recommended that non-destructive methods, such as acoustic and surface penetration radar techniques, be investigated for their ability to assess the condition of AC pipes. Such non-destructive and non-intrusive technologies will be instrumental in enhancing the amount and quality of pipe condition surveys conducted by utilities, leading to more effective asset management.

There is evidence to suggest that microbiological activity and biofilm development in drinking water distribution systems can attack AC pipes. Some bacterial groups are capable of producing short chain organic acids, lowering local (cement matrix) pH values and facilitating transformation and dissolution of the alkaline components of the hydrated cement matrix. The factors that contribute to biofilm development, and to pipe attack, still need to be more fully understood and applied.