NIST Technical Note 2088

Measurement Science Research Needs for Premise Plumbing Systems

Andrew Persily
David Yashar
Natascha Milesi Ferretti
Tania Ullah
William Healy

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2088

National Institute of Standards and Technology
U.S. Department of Commerce

NIST Technical Note 2088

Measurement Science Research Needs for Premise Plumbing Systems

Andrew Persily
David Yashar
Natascha Milesi Ferretti
Tania Ullah
William Healy
Energy and Environment Division
Engineering Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2088

May 2020

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Technical Note 2088
Natl. Inst. Stand. Technol. Tech. Note 2088, 79 pages (May 2020)
CODEN: NTNOEF

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2088

EXECUTIVE SUMMARY

Premise plumbing systems constitute an essential component of the built environment by providing immediate access to clean, potable water and a safe, reliable means of removing wastewater from homes, businesses and other institutions. Plumbing systems evolved extensively throughout the 20th century beginning with efforts in the 1920s to develop the technical understanding needed to support system design and regulation, much of which was initiated by then Secretary of Commerce Herbert Hoover to address a range of health and performance issues. Plumbing systems continue to evolve in response to current concerns about cost, water availability, environmental impacts and safety.

A series of policy actions including the Safe Drinking Water Act of 1974, the Energy Security Act of 1980 and the Energy Policy Act of 1992 sought to improve water quality, water use efficiency, and energy efficiency. These changes led to notable achievements including the reduction of lead in plumbing products and the introduction of low-flow fixtures. For example, a typical single-family, detached home today uses 22 % less water for indoor purposes than it did two decades ago (DeOreo, et al., 2016). As a result, the flow rates within the piping networks and the corresponding residence times can be significantly different than those assumed under current design methods. Consequently, the assumptions surrounding the effectiveness of water treatment practices are not necessarily applicable, leading to the potential for decreased water quality. These and other realities have led to a situation in which plumbing systems are being designed, installed and operated in vastly different ways from what is supported by the technical data and understanding embodied in current codes, standards and practice.

Plumbing design approaches, codes and standards have not kept pace with these changes, in large part because of the existence of significant technical knowledge gaps. Research is needed to address these gaps in support of water efficiency and water quality goals to ensure the effectiveness of these systems today and in the future. This report documents specific research needs to advance plumbing system design, operation and maintenance, as well as the standards, codes and guidelines that apply to these systems.

The primary concerns that motivated this effort to identify premise plumbing research needs are water quality, water efficiency, and energy efficiency. Water quality is one of the biggest concerns as it directly affects the health and safety of building occupants, and is becoming an increasingly complex challenge. Water quality concerns fall into three main categories: metallic, chemical, and biological. The need for water efficiency is expected to become more pressing as a result of population growth, climate change and infrastructure challenges. The availability of water is largely a regional issue, and there are many areas around the U.S. and throughout the world that are subject to recurring water shortages, even under non-drought conditions. Energy efficiency is another important driver for plumbing advancements. Every year, the United States spends over $400 Billion on energy in buildings (DOE, 2016; DOE, 2013). As a nation, almost half of all water use is for the production of electricity, and more than 3 % of electricity is used to move and treat potable water (DOE, 2014). As the plumbing community looks for ways to reduce water consumption, energy consumption must be considered given the strong coupling of water and energy use.

The purpose of this report is to identify measurement science research needs that are critical to the design of new premise plumbing systems and the operation and retrofit of existing systems to achieve the goals of water and energy efficiency and water quality in an integrated manner. The scope of this research needs assessment includes engineering issues related to system design and operation, and is motivated by the trends and drivers outlined above, particularly the need to update design methods, data, standards, and building codes to reflect the need to increase water efficiency and maintain water quality. The research needs do not focus on water quality, except to the degree that system design, operation, and maintenance impact these processes and the resultant water quality. The research needs also exclude water treatment processes and distribution systems serving buildings, except as these processes and systems impact conditions within buildings. The measurement science research needs in this report were identified with involvement of the broader stakeholder community as described below. While not intended to solely focus on needs in the United States, it should be noted that nearly all the input to this report was gained through interactions with U.S. stakeholders.

The research needs are categorized into 1) Foundational Measurement Science and 2) Applied Research. The Foundational Measurement Science needs include topics such as metrics, test methods, and data that are critical to understand and characterize the physical, chemical, and biological performance of plumbing systems. Applied Research builds on the findings of the Foundational Measurement Science topics to develop guidance and design approaches to improve the efficiency of the water delivery systems while also improving water quality.

Table ES-1 lists the research needs under Foundational Measurement Science, while Table ES-2 lists the Applied Research needs. For each of these needs, potential products including data, test methods, standards and guidance, are listed in Table ES-3.

While this report identifies many important research needs for premise plumbing, significant efforts are needed to implement these research activities. A number of steps are proposed to convert these research needs into actionable research programs. First, an implementation plan is needed to convert these needs into a detailed roadmap for defining future research programs and projects. This roadmap would include timelines for specific programs and projects, commitments by stakeholder organizations to take the lead on various elements, and specific deliverables expected from each effort. Developing this implementation plan and roadmap will require establishment of the priority of the research needs as well as consideration of the proper sequencing of research projects to achieve the ultimate goal of efficient and safe premise plumbing systems. As an example, foundational research is needed to develop metrics and data collection protocols prior to launching efforts to evaluate system performance and collect field data. The implementation plan must also identify the organizations that can sponsor and carry out the research. Finally, the plan must identify methods to disseminate the results of the research to key stakeholders who will make use of the information gained, such as standards developing organizations, professional societies that develop guidance and training programs, educational institutions that train designers and installers, and private sector firms that develop plumbing technology and design software. As noted earlier, the stakeholders who would be involved in developing the implementation plan and the research roadmap include manufacturers/trade associations, researchers, national and local government agencies, non-profit water efficiency advocates, water utilities, standards development organizations, model code bodies, code officials, educational institutions, engineering consultants, builders and developers, and others. This broad range of expertise and perspective needs to be engaged to fully cover the landscape of the research needs identified in this report and their implementation.

NIST intends to use the results of this research needs assessment to plan potential research activities in the area of premise plumbing, but NIST alone cannot meet the needs of the plumbing community in promoting efficient and safe water systems. Where appropriate to NIST's measurement science mission, NIST may identify areas in which can start to address some of these research needs. Other organizations, such as the U.S. EPA and the Water Research Foundation, may also use this assessment to identify potential areas for their research programs.

Table ES-1 Research Needs in Foundational Measurement Science

Area #F1: Terminology
Standardized definitions of key terms
Taxonomy of plumbing system design and layout
Area #F2: Metrics
Metrics for long-term durability and resilience
Chemical and biological attributes of influent water
Chemical and biological attributes of wastewater
Water quality targets specific to facility type
Metadata development
Area #F3: Data
Data on water demand patterns for various building types
Water use data to update Hunter's Curves
Water quality data at point of entry and point of use
Occupant behavior and preferences
Data on biofilm and scale development
Data on water conditions to support design and operation for OPPP control
Data quantifying system impacts on dissipation of chlorine and other disinfectants
Data on the effects of residence times on scaling and water quality
System design information following disease outbreaks
Area #F4: Flow and Transport Fundamentals
Hydrodynamic flow regimes and transport
Pressure losses as a function of materials and fitting geometry
Chemical processes in plumbing systems
Biological processes in plumbing systems
Plumbing material leaching
Material and chemical impacts on biofilms, pathogens and scaling
Impacts of residence time on water quality
Impacts of water source on water quality
Impacts of reduced flow rates on drainage system
Improved venting requirements based on modern system demands
Area #F5: Methods and Measurement
Methods to collect end use data
Test methods for water quality in supply and distribution systems
Performance of fittings and pipes
Protocol to describe plumbing design of existing buildings
Improved and less expensive meters
Area #F6: Model Development
Simulation tools of water flow, supply and drainage
Reference buildings and plumbing systems
Data to validate plumbing models
Expansion of plumbing models to include thermal analysis
Expansion of chemical and biological models
Models to estimate reduced drainage loads

Table ES-2 Applied Research Needs

Area #A1: System Design
New plumbing system designs and technologies
Validation of alternative sizing models and methodology for integration with plumbing codes
Potential side-effects of water and energy-efficient systems
Hot water plumbing design
Multipurpose residential piping and sprinkler systems
Comparison of trunk-branch and series distribution systems
Impacts of alternative water use
Impacts of design, reuse, reduced flows, materials, and water quality on wastewater systems
Area #A2: Installation, Operation and Maintenance
Impact of current plumbing codes and standards
Best practice guidelines for installation
Recirculation lines and temperature maintenance
Water management protocols for existing buildings
Water management strategies to control *Legionella* and other pathogens
Best practices for maintenance of emergency fixtures
Best practices for scheduled shutdowns and resiliency to unplanned disturbances
Metering for low-flow systems
Eliminating domestic galvanized iron pipe
Area #A3: Training and Guidance
Guidance for homeowners, facility managers and other practitioners
Training for designers on water efficiency
Training and certification for design, operation and maintenance
Training for building water system assessments
Maintenance and monitoring guidance for control of *Legionella* and other OPPPs

Table ES-3 Potential Products of Identified Research Needs

Fundamental Measurement Science
Area #F1 Terminology: • Technical report of draft terminology and definitions • Consensus standard or guideline on premise plumbing terminology • Taxonomy for describing plumbing system layout • Protocol for characterizing premise plumbing system layout • Consensus standard or guideline for characterizing and describing plumbing system layouts
Area #F2 Metrics: • Technical report describing metrics and other key performance factors, including system durability and resilience and influent and wastewater chemical and biological characteristics • Consensus standard or guideline defining metrics and other key performance attributes • Candidate water quality targets for different types of facilities, leading to consensus standards and guidelines to meet these targets • Technical report describing building metadata for plumbing system performance characterization, leading to consensus standards and guidelines

Area #F3 Data:
• Nationally-representative databases of water use and water quality for commercial, residential, and institutional buildings, including:
  o Water use data to validate updated sizing models
  o Water quality data at POE and POU
• Research studies on how system factors, including residence time, influence biofilms and scaling, impact water quality
• Research studies on the impacts of design on the dissipation of chlorine and other disinfectants
• Research studies on the impacts of system design and water conditions on OPPPs
• Research studies of how building occupants use water that provides an understanding of their preferences and how these preference can change over time
• Plumbing system design information from disease outbreaks
• Design guidance to address system residence times, particularly in low water use buildings

Area #F4 Flow and Transport Fundamentals: • Improved understanding, data and models of water flow in plumbing and wastewater systems • Detailed hydrodynamic models of water flow in plumbing systems • Methods of test to measure pressure drop through plumbing fittings and components • Improved understanding of chemical and biological processes in plumbing systems, including the effects of materials, disinfectant levels, water flow and other system parameters • Improved models of chemical and biological processes in plumbing systems • Better methods to measure material leaching into water from plumbing system components and models to predict these processes • Technical data characterizing scale formation and biofilm and bacterial growth rates in piping networks, including characterization of microbial nutrients, chlorine residual decay, temperature, flow rate, residence time, materials, system age, and other relevant issues • Models to predict scale formation and biofilm and bacterial growth in plumbing systems • Data on the impact of water sources on water quality in plumbing systems • Data to support updated vent sizing requirements in drainage systems

Area #F5 Measurement Methods:
• Test methods and protocols for conducting field surveys of water use and water quality in buildings • Test methods for characterizing the performance of fittings and pipes • Protocols to identify and describe plumbing system designs in existing buildings • Performance specifications for water meters • Prototype meters for improved and lower-cost real-time monitoring. • Guidelines on field data collection methods • Guidelines for the installation and use of continuous, real-time meters
Area #F6 Model Development:
• Improved algorithms and simulation programs to model water hydraulics, as well as chemical and biological processes in plumbing systems • Plumbing system design tools that integrate with BIM platforms • Reference building models, including plumbing systems, for use in simulating the impacts of different technologies and design approaches • Datasets for validating plumbing simulation model predictions of hydraulics and water quality • Addition of thermal analyses to plumbing system models • Enhancement of the chemical and biological capabilities of EPANET • New probabilistic models to estimate drainage loads

Applied Research
Area #A1 System Design Issues
• Assessment of new plumbing technologies and design approaches, including trends in their development and application • Validated sizing methods for incorporation into plumbing codes • Technical data on temperature and other performance parameters in water- and energy-efficient plumbing systems, including information on potential side effects of temperature settings on water quality and materials • Technical data from comparison of traditional dead-end and closed-loop distribution systems • Technical data on the development of OPPPs in combined hydronic/potable systems • Technical data on impacts of new supply-side technologies on wastewater systems, including information to support pipe design guidance to ensure drainage performance • Technical assessment of alternative water systems, e.g., rainwater harvesting and on-site reuse • Design and installation guidance for water heaters and hot water distribution systems • Design strategies that reduce water use and minimize development of OPPPs • Design and installation guidance for alternative water systems
Area #A2 Best Practice for Installation and Operations
• Analysis of the impacts of current design practice and code enforcement on plumbing system performance • Analysis of the impacts of plumbing system installation on performance, including the impacts of value engineering during construction and renovation • Assessment of current O&M practice with the goal of providing improved O&M tools • Investigation of current practice on recirculation lines and temperature maintenance systems and their impacts on water quality and other aspects of system performance

- Analysis of impacts of changes in building use on plumbing system performance, leading to water management protocols for existing buildings
- Technical data and guidance on meter sizing for low-flow systems
- Technical data on flushometer valve design for low-flow systems
- Literature review of international research and practice on water management
- Technical assessment of the effectiveness of onsite water treatment and other management programs, leading to strategies to increase the implementation of best practices including maintenance to control *Legionella* and other OPPPs
- New software tools to address water management and water safety plans that could be integrated into building management software
- Best practices for maintenance of emergency fixtures
- Best practices for planning for scheduled shutdowns and ensuring resiliency
- Policies and regulations to support the elimination of domestic galvanized iron pipe

Area #A3 Training and Guidance

- Guidance on premise plumbing operation and maintenance for building owners and operators, including homeowners
- Training on water efficient plumbing system design
- Training and certification programs that address design, operation and maintenance of plumbing systems
- Training for conducting building water system assessments
- Training and guidance on best practices for system maintenance and monitoring to control *Legionella* and other OPPPs

ABSTRACT

Premise plumbing systems provide key building services and exist in the context of a range of performance goals including energy efficiency, water efficiency, reduced environmental impacts, and occupant health and comfort. Pressures to improve water efficiency and increasing awareness of the importance of building water quality, combined with the use of new materials and plumbing design concepts, have led to the recognition of significant knowledge gaps in premise plumbing system design, installation, operation and maintenance. In addition, current design approaches are based on old technical data, higher water flow rates than those existing in many current buildings, and materials that have been replaced by newer alternatives. Advancements are overdue for design methods and data to support current and future design goals, including those that integrate new plumbing system concepts and materials. A wide range of stakeholders have identified research topics that need to be addressed to support these advancements, including fundamental hydraulic and transport processes in plumbing systems, material interactions with disinfectants and other substances in water systems, new modeling and design methods, building water use patterns and other critical performance data, and the need for updated standards, codes and other guidance for designers, building owners and occupants. This report presents research needs to support future programs intended to fill these knowledge gaps and is based on a 2018 workshop sponsored by NIST, EPA and WRF, a call for research needs posted in the Federal Register, and other discussions with stakeholders. This document is intended to assist these organizations and others in planning future research programs that support the implementation of premise plumbing systems that achieve water efficiency and water quality goals into the future.

NOMENCLATURE

ANSI: American National Standard International
ASA: American Supply Association
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME: American Society of Mechanical Engineers
ASPE: American Society of Plumbing Engineers
ASSE: American Society of Sanitary Engineers
AWWA: American Water Works Association
BIM: Building information modeling
BOCA: Building Officials and Code Administrators
CFD: computational fluid dynamics
DFU: Drainage Fixture Unit
DOE: Department of Energy
EPA: U.S. Environmental Protection Agency
FRN: Federal Register Notice
GBI: Green Building Institute
IAPMO: International Association of Plumbing and Mechanical Officials
IBC: International Building Code
ICBO: International Conference of Building Officials
ICC: International Code Council
IgCC: International Green Construction Code
IPC: International Plumbing Code
IRC: International Residential Code
NBS: National Bureau of Standards
NIST: National Institute of Standards and Technology
NSF: National Sanitary Foundation International
NZERTF: Net-Zero Energy Residential Test Facility
OPPP: opportunistic premise plumbing pathogens (sometimes referred to as OP and OPP)
O&M: operations and maintenance
PILC: Plumbing Industry Leadership Coalition
POE: point of entry
POU: point of use
ReNEWW: Retrofit Net-Zero: Energy, Water, and Waste
RESNET: Residential Energy Services Network
SDO: Standards Development Organization
SBCCI: Southern Building Code Congress International
UPC: Uniform Plumbing Code
USGBC: U.S. Green Building Council
WEStand: Water Efficiency and Sanitation Standard for the Built Environment
WRF: Water Research Foundation

TABLE OF CONTENTS

INTRODUCTION

Premise plumbing systems constitute an essential component of the built environment by providing immediate access to clean, potable water and a safe, reliable means of removing wastewater from homes, businesses and other institutions. Plumbing systems evolved extensively throughout the 20th century in response to concerns about cost, water availability, environmental impacts and safety, including efforts to address water efficiency and water quality. However, plumbing design approaches, codes and standards have not kept pace with these changes, in large part because of the existence of significant technical knowledge gaps. Research is needed to address these gaps in support of water efficiency and water quality goals to ensure the effectiveness of these systems today and in the future. This report documents specific research needs to advance plumbing system design, operation and maintenance, as well as the standards, codes and guidelines that apply to these systems.

Historical Perspective

The introduction of plumbing systems into buildings constituted a tremendous advance in public health, safety, and comfort. However, a number of challenges arose in the building sector following World War I, including the need for more uniformity in local building and plumbing codes. These challenges led Secretary of Commerce Hebert Hoover to create in 1921 a building and housing division within the National Bureau of Standards (NBS), the predecessor to the National Institute of Standards and Technology. Motivations for this new division included "poor home designs, high labor and material costs, antiquated and obstructive building codes and zoning regulations" (Cochran, 1966).

Specific to plumbing, system failures and contamination were among the many challenges facing premise plumbing in the late 19th and early 20th century. For example, very little was known about how building occupants used water, unnecessarily restrictive code requirements were expensive to implement, and health and safety concerns were not being adequately addressed (Whipple, et al., 1924). Leakage was common both within dwellings and in the ground outside, which resulted in foodborne illness through the medium of insects and polluted water supplies such as neighboring wells. Air pockets were common within plumbing supply and drainage systems, which allowed insects and vermin to become rampant within the systems and transmit disease. Uninformed installation practices often resulted in water supply lines being cross contaminated with drain and/or sewage lines, and it was common for wastewater backflow to pollute faucet taps. Furthermore, noxious and/or combustible gasses were routinely entering buildings from the sewage system. The 1924 Whipple report to the Department of Commerce discusses these issues and other motivations for government involvement in plumbing codes.

In that 1924 report, Secretary Hoover stated "Actual practice has been governed by opinions and guesswork, often involving needless costly precautions which many families could ill afford. The lack of generally recognized principles is responsible to a certain extent for the contradictory plumbing regulations in different localities." To help industry become more profitable and efficient, he organized a group of industry experts to form the Department of Commerce's Building Code Committee to help address the chronic problems with premise plumbing systems. When they found that minimum requirements could not be determined from existing codes, Secretary Hoover called for NBS to conduct experiments to investigate the underlying principles of house drainage under the supervision of a subcommittee of sanitary engineers and plumbers.

As a result, the first plumbing code was published in 1928, commonly referred to as the Hoover Report or Hoover Code (Whipple, et al., 1928). This prescriptive code established 20 basic principles of plumbing systems as well as minimum technical requirements to achieve safe and healthy systems. Many engineers, plumbing inspectors, plumbers, and architects provided data and reviewed recommendations in the development of this code. Dr. Roy B. Hunter was the NBS scientist who performed the research that transformed this industry from the 1920s to the 1940s. Dr. Hunter's most significant contribution was a model to predict the demands on a plumbing system based on the number and types of fixtures, known as Hunter's Curve, which is still used today (Hunter, 1940). However, Dr. Hunter indicated that some code provisions should be studied further and identified the need to evaluate the physics of plumbing systems to inform a performance-based method. This work was not carried out due to the death of Dr. Hunter, though the need for a performance-based method remained.

In conjunction with these federal activities, other efforts were undertaken to reduce problems and standardize practices in building safety and construction, including the formation of the Building Officials and Code Administrators (BOCA) in 1915 and the International Association of Plumbing and Mechanical Officials (IAPMO) in 1926 (Harkness, 1995). These industry efforts, supported by research at NBS and other organizations, helped develop the plumbing codes and standards upon which premise plumbing designs have delivered potable water and removed waste from buildings to this day.

After WWII, reconstruction efforts in Europe resulted in international cooperation that facilitated the development and adoption of building standardization practices (Tranchard, 2017). Plumbing systems were seen as essential to buildings, and significant efforts were devoted to lowering the cost of materials, installation, and maintenance of plumbing systems; to developing new and innovative fixtures, features, and appliances connected to the systems; to using new materials; and, to conserving water and energy (Perrier, 1979). As the 20th century progressed, new international platforms provided for the effective exchange of building research data and technical expertise. The International Council for Building Research (CIB) Committee W-62 was formed in 1972 and focused on research to develop standards for water supply and drainage in buildings (Galowin and Debelius, 1979). It was widely acknowledged that European experience could be quite useful in updating U.S. plumbing design (Raley, 1973).

In the 1970's, NBS recognized the need for performance standards to replace the largely prescriptive approach of existing codes and that efforts to update Hunter's Curve were lacking fundamental data. Researchers found that the actual water demand in installations was considerably less than the predictions used to select pipe sizes and that research was needed to update load predictions for plumbing systems. As noted in (Orloski and Wyly, 1978), "In recent times, engineers have metered the building water service on various occasions in limited studies to compare observed peak demand with that predicted from the Hunter Curve. Generally, they have found the actual demand to be considerably less than that predicted from the Curve. However, there has been no work to systematically adjust the currently used values of the basic parameters of the Hunter model … that determine the predicted hydraulic load. Rather, only empirical modifications of the ordinate of the curve have been suggested. A long-range comprehensive national field program is needed. This work should use uniform, technically adequate methods of experimental design, data acquisition and analysis, and should involve all groups having a substantial interest in the subject of updating load prediction for plumbing systems (e.g., updating of the Hunter Curve)." Galowin, et al. (1979) summarized the problem of relying on the original Hunter's Curve: "The reliance upon traditional codes which specify allowable configurations and designs, pipe sizes and materials inhibits implementation of innovative solutions for water supply and drainage systems and for water conservation practices, and limits materials resource conservation and energy conservation opportunities. The consequences are overdesign of traditional systems and delay or difficulty in gaining acceptance of innovative approaches."

Standards organizations dedicated efforts to developing performance standards, recognizing that existing data and professional judgement would be the foundation of such standards until basic knowledge of the relevant physical and chemical phenomena advanced. That knowledge, together with analytical modeling or testing methods could provide a more definitive and meaningful basis for reproducible evaluation techniques and quantitative criteria. To this day, these knowledge gaps still exist, and the plumbing codes remain largely prescriptive.

Current Trends and Drivers

A series of policy actions including the Safe Drinking Water Act of 1974, the Energy Security Act of 1980 and the Energy Policy Act of 1992 sought to improve water quality, water use efficiency, and energy efficiency. These changes led to notable achievements including the reduction of lead in plumbing products and the introduction of low-flow fixtures. For example, a typical single-family, detached home today uses 22 % less water for indoor purposes than it did two decades ago (DeOreo, et al., 2016). As a result, the flow rates within the piping networks and the corresponding residence times are significantly different than those assumed under current design methods. Consequently, the assumptions surrounding the effectiveness of water treatment practices are not necessarily applicable, leading to the potential for decreased water quality. These and other realities have led to a situation in which plumbing systems are being designed, installed and operated in vastly different ways from what is supported by the technical data and understanding embodied in current codes, standards and practice.

The primary concerns that motivated this effort to identify premise plumbing research needs are water quality, water efficiency, and energy efficiency. Water quality is one of the biggest concerns as it directly affects the health and safety of building occupants, and is becoming an increasingly complex challenge. Water quality concerns fall into three main categories: metallic, chemical, and biological. The primary metal of concern for drinking water quality problems is lead (EPA, 2019). Lead is a serious hazard with known health effects and, unfortunately, it is still present in many water systems at unsafe levels (LSLR, 2020). Lead was commonly used in many water distribution systems and in products integrated as part of plumbing systems but was banned in 1986 as understanding of the dangers of lead exposure increased. However, lead persists as a problem, partially due to the inability to remove lead from existing infrastructure, and partially due to the limited technical understanding of how lead leaches into water. Furthermore, since the health effects of lead can be difficult to detect at the onset, lead exposure can proceed unidentified for extended periods of time (CDC, 2020).

Chemical contaminants are another concern as they can significantly alter water quality in plumbing systems. For example, some of the chemicals used to treat potable water may react with materials used within plumbing system networks, and the reaction by-products may have significant health or material durability impacts. Also, some of these chemical contaminants are being found in water supply lines (Lytle and Liggest, 2016; Whelton and Nguyen, 2013). There needs to be a better understanding of the interaction between the chemicals used to treat potable water and the materials used within plumbing networks, including the impact of these reactions on water quality and the long term durability of materials.

Biological contaminants within plumbing systems are of increasing interest, and research indicates that plumbing system design may be a contributing factor (Falkinham, et al., 2015; Prest, et al., 2016; Brazeau and Edwards, 2013; National Academies of Sciences, 2019; National Research Council, 2006). Among the issues related to biological contaminants is the lack of understanding of water residence times in distribution networks and premise plumbing systems, the mechanisms by which stagnant water interacts with the materials in the systems, and how the physical configuration of premise plumbing systems create conditions conducive to bacterial growth. These knowledge gaps are impeding the development of effective treatment plans to control biological contaminants.

The need for water efficiency is expected to become more pressing as a result of population growth, climate change and infrastructure challenges. The availability of water is largely a regional issue and there are many areas around the United States and throughout the world that are subject to recurring water shortages, even under non-drought conditions (Miller, 2019; Welch, 2018; DeOreo, et al., 2016; Mayer, et al., 1998; Maupin, et al., 2014).

Obviously, technologies, designs and practices that reduce water consumption are valuable. During the past few decades, substantial changes to the products used in plumbing systems have occurred with the goal of reducing water consumption. The Energy Policy Act of 1992 required significant reductions in water used by toilets, faucets, showerheads and other fixtures, and the impact of this act has been a successful reduction in water consumption (DeOreo, et al., 2016). However, there is a need to understand the impacts of these reductions on water conditions within plumbing systems as well as overall system performance. Water is being transported at much lower flow rates through plumbing systems than previously, but plumbing systems are designed using prescriptive codes that do not fully account for increased water efficiency in fixtures and appliances. There are potential negative consequences to these changes if water systems become microbial reservoirs as low flow or stagnant conditions provide more time for bacteria to grow inside plumbing systems and for the breakdown of disinfectant residual levels. Low flows also allow for more time for chemical reactions to take place, and more opportunity for materials to dissolve into the water.

It is worth noting that many discussions of buildings with low water use refer to “green buildings,” and that some research efforts have identified important water quality issues in such buildings (Rhoads, et al., 2016; WRF, 2019a). It is important to understand that the term green buildings, while not always consistently defined and used, addresses many aspects of building performance including site sustainability, energy efficiency, indoor environmental quality and resource and material conservation, in addition to water efficiency (ASHRAE, 2017). Rather than simply attributing these water quality issues to green buildings, it is more accurate and useful to refer to these issues as potentially being linked to buildings that utilize specific technologies, designs, or O&M strategies that result in low water use, low flow rates and/or high water residence times.

Furthermore, water-stressed areas have been considering water reuse for a variety of potable and non-potable uses. While this approach can reduce water use in buildings, the application of reuse requires technical information to achieve its goals safely and effectively. Clearly, identifying appropriate uses and strategies for reuse is important, but the impact of reuse on the rest of the plumbing system can be significant and must be considered.

Energy efficiency is another high priority driver for plumbing advancements. Every year, the United States spends over $400 Billion on energy in buildings (DOE, 2016; DOE, 2013). As a nation, almost half of all water use is for the production of electricity, and more than 3 % of electricity is used to move and treat potable water (DOE, 2014). As the plumbing community looks for ways to reduce water consumption, energy consumption must be considered because of the strong coupling of energy and water use. For example, water heating is the second largest end use of energy within buildings, therefore reducing hot water use will significantly lower building energy consumption. Furthermore, when hot water is stored within and transported throughout a building it loses heat to its surroundings, which adds to the building's thermal load and requires more operation of the water heating system and the HVAC equipment used to maintain indoor thermal conditions. Efforts to conserve both energy and water will interact as a result of both the direct and indirect relationships between water and energy use.

Other Calls for Research

Several organizations in both the public and private sectors have recognized the need to advance the state of knowledge with regards to premise plumbing systems, and more broadly water distribution systems.

The National Institute of Building Sciences (NIBS) assembled a group of industry leaders in 2016 to examine the trends that hinder realization of high-performance buildings and communities (NIBS, 2016). That group identified several measurement science needs related to premise plumbing systems to improve water use efficiency, protect against human exposure to waterborne diseases, reduce energy consumption, and save energy and money.

The National Academies published two reports that outline research needed to advance plumbing systems and improve the health and safety of the people who rely on them. A report titled "Drinking Water Distribution Systems: Assessing and Reducing Risk" was published in 2006 (National Research Council, 2006). While this report focused on the distribution systems (outside of the property lines), the connections and relationships to the premise plumbing systems (inside of the property lines) are considered throughout the report and many of the knowledge gaps identified are relevant in both domains. This report proposes dozens of recommendations to improve protections from pathogens, physical resilience of the systems, design and maintenance of systems, and water quality.

In 2019, the National Academies published "Management of *Legionella* in Water Systems", which addressed the bacteria that can infect people with Legionnaires' disease (National Academies of Sciences, 2019). This document describes all of the attributes of design, materials, operation, and maintenance within plumbing systems that play a significant role in the lifecycle of *Legionella* bacteria, and ultimately focuses on seven different recommendations for research, guidance, and education related to plumbing systems that are intended to reduce the risk of infection. These recommendations are:

- Maintain water heater temperatures above 60 °C (140 °F)
- Consider monochloramine instead of free chlorine to treat water
- Conduct research to increase understanding of disinfectant decay in building plumbing systems
- Produce guidance about *Legionella* for homeowners
- Eliminate low-flow fixtures in buildings with high-risk occupants
- Conduct research to enable new designs for cooling towers and humidifiers
- Incorporate risk factors for *Legionella* growth into green building criteria to ensure that these are not compromised for conservation goals

The Water Research Foundation has published at least three reports that specify research needs related to premise plumbing systems. The first of these, WRF Project 4379, State of the Science and Research Needs for Opportunistic Pathogens in Premise Plumbing, includes a comprehensive literature review and a list of 20 recommended projects that include engineered controls of opportunistic pathogens (WRF, 2019c). The following topics identified in that report are consistent with the scope of the current effort and are captured in the Research Needs herein:

- Relationship between distribution system and microbiota of premise plumbing
- Fundamental factors/mechanisms controlling detachment and release of OPPPs from biofilms in premise plumbing
- Impact of water treatment on control of OPPPs in premise plumbing
- Optimizing the design of hot water systems to achieve temperature control of OPPPs and prevent amplification
- Understanding chlorine, chlorine dioxide and chloramine demand in hot water premise plumbing
- Determining why electronic faucets sometimes harbor high levels of OPPPs
- Potential contribution of disinfection and other management practices on emergence of multi-antibiotic resistant pathogens
- Secondary impacts of in-building disinfection on corrosion of galvanized iron, stainless steel, copper, and brass.

WRF Project 4383, Green Building Design: Water Quality Considerations, discusses water quality problems related to green buildings in which water use is reduced (WRF, 2019a). Specifically, this document outlines differences between plumbing related issues in what they refer to as green buildings and traditional buildings. Some examples include reduced effectiveness of disinfectants such as chlorine and chloramine due to the lower water consumption rates, corrosion, taste and odor, and microbiological contaminants. This document also includes an outline of the relevant codes and how they impact green building design.

WRF Project 4606, Research Plan for Management of Emerging Pathogens Associated with Distribution Systems, includes 15 different project topics that relate to premise plumbing systems (WRF, 2019b). The research topics identified in that report related to measurement science needs for plumbing systems covered in the current report include:

- Operational and design considerations for controlling opportunistic pathogens in hot water heaters and premise plumbing
- Risk-based exposure model for pathogenic *Legionella* in premise plumbing
- Evaluation of premise plumbing flushing strategies
- Premise plumbing pipe materials assessment to promote development of best management practices

Scope of Measurement Science Research Needs Assessment

The purpose of this report is to identify measurement science research needs that are critical to the design of new premise plumbing systems and the operation and retrofit of existing systems to achieve the goals of water and energy efficiency and water quality in an integrated manner. The scope of this research needs assessment includes engineering issues related to system design and operation, and is motivated by the trends and drivers outlined above, particularly the need to update design methods, data, standards, and building codes to reflect the need to increase water efficiency and maintain water quality. The research needs do not focus on water quality, except to the degree that system design, operation, and maintenance impact these processes and the resultant water quality. The research needs also exclude water treatment processes and distribution systems serving buildings, except as these processes and systems impact conditions within buildings. The measurement science research needs in this report were identified with involvement from the broader stakeholder community as described below. While not intended to solely focus on needs in the United States, it should be noted that nearly all the input to this report was gained through interactions with U.S. stakeholders.

Sources of Information Used in Identifying Research Needs

Several sources of information were used to identify the research needs presented in this report, including the following:

- NIST, EPA, and WRF jointly hosted a workshop in August 2018 to identify and discuss research needs to support the design and operation of new premise plumbing systems and the management of existing systems in light of lower water consumption and the need to ensure water quality at the point of use. The proceedings of this workshop, Measurement Science Roadmap Workshop for Water Use Efficiency and Water Quality in Premise Plumbing Systems, are available at https://doi.org/10.6028/NIST.GCR.19-020 (Pickering, et al., 2018). This event was attended by 46 representatives from industry, academia, government, utilities, standards and codes organizations, and other research and stakeholder organizations. During this workshop, 48 unique research needs were identified, which are listed in Appendix A of this report.
- NIST solicited input from the public through a request for information (RFI) that was published in the Federal Register in October 2018 (https://www.nist.gov/el/energy-and-environment-division-73200/rfi-response). This RFI received 26 responses from a broad array of interested parties, generating over 140 pages of text in response to the request for the

most important issues to design and operate safe, healthy, reliable, and efficient plumbing systems and the research needed to address these issues. A summary of the information received through this RFI is presented in Appendix B of this report.

- Additional discussions with stakeholders were also an important source of information in this report. For example, IAPMO and ICC are the two major model code development organizations within the premise plumbing community, and discussions with both provided substantial input to this document. Follow up discussions with the WRF, EPA, numerous advocacy groups, and academic researchers were also a key source of information.

The stakeholders engaged by NIST to inform this research needs assessment and identify participants in the August 2018 workshop, as well as those who responded to the 2018 RFI, included a broad range of representatives including manufacturers, trade associations, researchers, national and local government agencies, non-profit water efficiency advocates, water utilities, standards development organizations, model code bodies, engineering consultants, and others. This broad range of expertise and perspective helped NIST cover the landscape of the issues discussed in this report. This collection of stakeholders is referred to as the "plumbing community" in this report. The figure below is from a 1978 NBS report (Orloski and Wyly, 1978) that shows the plumbing community as conceived of at that time, and which serves as an interesting representation of the community and the incorporation of hand-drawn graphics into reports during that era.

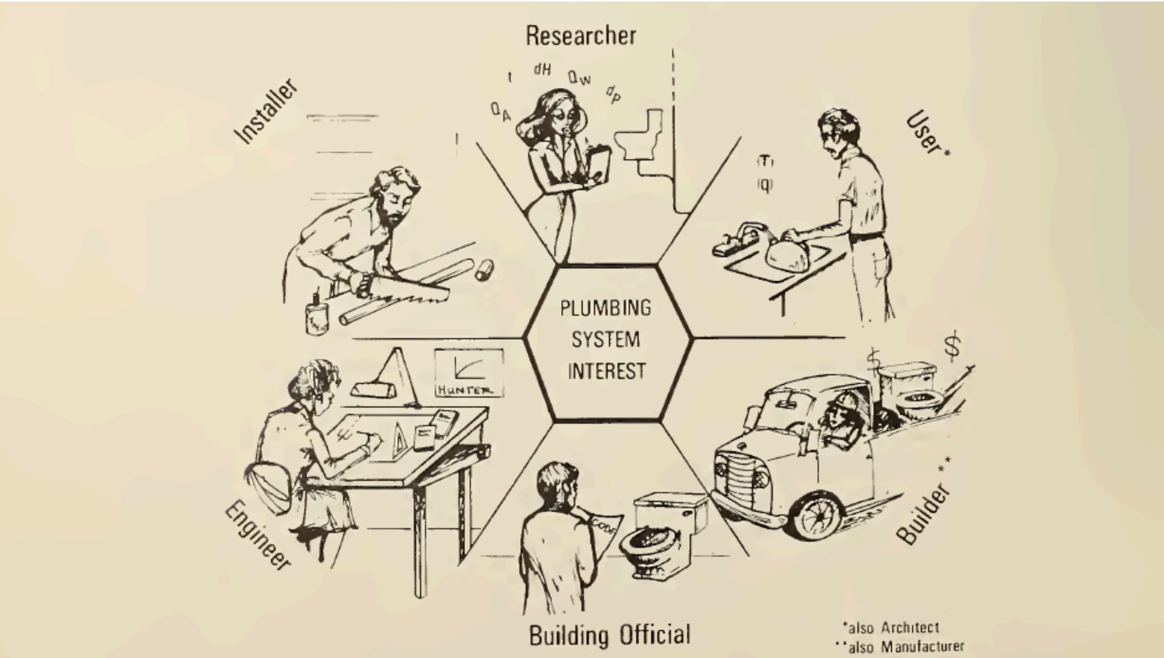

Figure 20. Schematic Indicating Groups Representing Cross-Section of Interests in Plumbing System Specifications

BACKGROUND

This section provides information on the current state of several key aspects of premise plumbing system design, analysis and research, beginning with a description of codes and standards. This discussion is followed by an overview of plumbing system design that highlights areas where new information is needed. In addition, this section describes current design and analysis tools, reviews plumbing system modeling studies, and discusses research facilities and projects that are being used to investigate premise plumbing system issues.

Codes and Standards Landscape

A summary of key standards and codes as they pertain to the design and operation of plumbing systems in buildings is presented here. The Alliance for Water Efficiency also provides an overview of the current Standards and Codes landscape related to premise plumbing (https://www.allianceforwaterefficiency.org/resources/green-building). ASSE International also published a range of product and professional standards (https://www.asse-plumbing.org/asse/standards/about), with more detailed provided below. The American Water Works Association (AWWA) maintains a large number of standards covering water utilities, including water treatment methods and specifications for the distribution of treated water to end users (https://www.awwa.org/Publications/Standards). However, those AWWA standards are out of the scope of the present discussion unless otherwise noted.

Plumbing Design Codes

The Hoover Code was the precursor to the American Standard National Plumbing Code, ASA A40.8-1955 (ASME, 1955). This code was widely accepted until it was withdrawn in 1972, at which point four organizations worked to have their model codes accepted nationally. Regional codes instead emerged, including: the National Plumbing Code (NPC) developed by the Building Officials & Code Administrators International (BOCA) adopted mainly in the eastern U.S.; the Standard Plumbing Code (SPC) developed by the Southern Building Code Congress International (SBCCI), adopted mainly in the southern U.S.; the Uniform Plumbing Code (UPC) developed by the International Association of Plumbing and Mechanical Officials (IAPMO), adopted mainly in the western U.S.; and the National Standard Plumbing Code developed by the Plumbing-Heating-Cooling Contractors National Association (PHCC), adopted in several U.S. states. As recently as the 1990's, there were five model plumbing codes in the U.S. In 1994, the International Code Council (ICC) was founded by BOCA, ICBO, and SBCCI to develop a combined set of coordinated national model construction codes that included the International Plumbing code (IPC). However, to this day, a single plumbing code is not universally recognized. In addition, there is a lag in the adoption of the latest model codes by local jurisdictions, as well as local variation in how model codes are adopted, modified, and enforced.

Currently, the design of premise plumbing systems in the U.S. is typically based on one of two model plumbing codes: the International Plumbing Code or the Uniform Plumbing Code. The International Plumbing Code "sets minimum regulations for plumbing systems and components to protect life, health and safety of building occupants and the public" (ICC, 2015). The Uniform Plumbing Code has a stated purpose to serve as "an ordinance providing minimum requirements and standards for the protection of the public health, safety, and welfare" and a scope that applies to "the erection, installation, alteration, repair, relocation, replacement, addition to, use, or maintenance of plumbing systems" (IAPMO, 2018). These codes still rely heavily on research done in the 20th century. For example, Hunter's Curve still provides a design demand value, based on the number of fixture units, while the governing code also specifies the number of fixtures required for the project, with these values varying from code to code.

Efforts have also been undertaken to develop plumbing design standards that go beyond minimum requirements. IAPMO recently published the Water Efficiency and Sanitation Standard for the Built Environment or WE•Stand (IAPMO, 2017). As stated in the document, "The purpose of this standard is to provide minimum requirements to optimize water use practices attributed to the built environment while maintaining protection of the public health, safety and welfare", and it was developed "in recognition that with increasing demand, constrained infrastructure and supplies, and pervasive droughts globally, there is a critical need to reduce water consumption attributed to the built environment through conservation and reuse." WE•Stand replaced the Green Plumbing and Mechanical Code Supplement and is noteworthy as it is the first ANSI standard that focuses solely on achieving safe and efficient water use in both residential and non-residential buildings.

Whole Building Standards and Codes that Address Water Efficiency

Water efficiency is incorporated in a number of green building standards and codes. ICC's International Green Construction Code, which incorporates ANSI/ASHRAE/ICC/USGBC/IEC Standard 189.1 Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings as its technical content (ASHRAE, 2017), contains a chapter devoted to water use efficiency (ICC, 2018b). ANSI/GBI 01-2019: Green Globes Assessment Protocol for Commercial Buildings "provides a method of assessing commercial buildings in relation to commonly valued environmental and efficiency outcomes (GBI, 2019)" and includes a chapter on water efficiency. On the residential side, ICC/ASHRAE 700-2015: National Green Building Standard was developed in conjunction with the National Association of Home Builders with the purpose to "establish criteria for rating the environmental impact of design and construction practices to achieve conformance with specified performance levels for green residential buildings (ICC, 2016)." Chapter 8 of this standard focuses on water efficiency.

Specific to water efficiency, ASHRAE is leading an effort co-sponsored by the American Society of Plumbing Engineers and the American Water Works Association to develop Standard 191: Standard for the Efficient Use of Water in Building Mechanical Systems. This standard will focus on providing minimum requirements for the design of mechanical systems that limit the volume of water required to operate HVAC systems.

Another recent standard, ANSI/RESNET/BICC: Standard 850-2020 Standard for the Calculation and Labeling of the Water Use Performance of One- and Two-Family Dwellings Using the Water Rating Index (ICC, 2020), was approved in April 2020 and sets the technical specifications for calculating the rating of a home's water efficiency.

At the state level, California maintains the California Green Building Standards Code, also known as the CALGreen Code (CBSC, 2016). This code aims to "improve public health, safety and general welfare by enhancing the design and construction of buildings through the use of building concepts having a reduced negative impact or positive environmental impact" in categories that include water efficiency and conservation.

Fixture Performance

The American Society of Mechanical Engineers' (ASME) committee A112: Plumbing Materials and Equipment has worked with the Canadian Standards Association (CSA) to develop a range of standards dictating key features and expected performance of a variety of plumbing fixtures. Examples include ASME A112.18.1/CSA B125.1: Plumbing Supply Fittings and ASME A112.18.2/CSA B125.2: Plumbing Waste Fittings (ASME, 2018; ASME, 2015). Another ASME Committee, B16, maintains standards covering valves, flanges, pipe fittings, gaskets and valve actuators for use in pressure services. ASTM International publishes a number of standard specifications for piping made of different materials such as polyvinyl chloride, crosslinked polyvinyl chloride, and crosslinked polyethylene. ASSE International also maintains a suite of standards on the performance of plumbing fixtures that "detail how a product is intended to function under normal operating conditions and include testing procedures and requirements for performance, health and safety." These standards can be accessed at https://www.asse-plumbing.org/asse/standards/product/current-standards.

In the United States, the Department of Energy regulates the maximum water use of a number of fixtures as legislated by the Energy Policy Act (U.S. Congress, 2005). The Environmental Protection Agency sponsors the WaterSense program (https://www.epa.gov/watersense), which is a voluntary program that aims to encourage the use of water-efficient products through labeling and presentation of resources for using water efficiently. Specifications include performance criteria to address user satisfaction issues; the performance of those products is based on standardized test methods from industry organizations such as ANSI, ASME, ASSE, ASTM, CSA, IAPMO and NSF.

Water Quality

A number of organizations maintain standards for water quality in buildings. Large keepers of such standards are ASSE International and NSF International, formerly known as the National Sanitary Foundation. Among the standards for water supply quality are NSF/ANSI/CAM 61: Drinking Water System Components (NSF, 2018a), and NSF/ANSI 14: Plastic Pipe and Fittings (NSF, 2018b). NSF International also has a number of standards related to wastewater, including NSF/ANSI 40: Residential Wastewater Treatment Systems "contains minimum requirements for residential wastewater treatment system having rated capacities between 1514 L/day and 5678 L/day (NSF, 2018c)." NSF/ANSI 350 and 350-1: Onsite Water Reuse establishes "material, design, construction and performance requirements for onsite residential and commercial water reuse treatment systems (NSF, 2017; NSF, 2019)." Under development by NSF in conjunction with ASHRAE is ASHRAE/NSF 514: Prevention of Injury and Disease Associated with Building Water Systems. This standard will coordinate with ASHRAE Standard 188: Legionellosis: Risk Management for Building Water Systems (ASHRAE, 2018), which "provides minimum legionellosis risk management requirements for the design, construction, commissioning, operation, maintenance, repair, replacement, and expansion of new and existing buildings and their associated (potable and non-potable) water systems and components."

The ASSE/IAPMO/ANSI 12000 series of professional qualification standards (https://www.asse-plumbing.org/asse/standards/pq/current-standards#) "addresses the need for construction and maintenance personnel to become proficient in identifying and managing potential situations where they may be exposed to pathogens, diseases and hazards," and more recently "defines general knowledge requirements for developing and implementing water systems risk management programs and sets minimum criteria for training and certifying employers, plumbers, pipefitters, HVAC technicians, and sprinkler fitters." One notable standard recently added to this series is ASSE/IAPMO/ANSI 12080, Professional Qualifications Standard for Legionella Water Safety and Management Personnel (ASSE, 2020).

Premise Plumbing Design Process Overview

To ensure that a building's plumbing system meets the project requirements, the plumbing design process requires collaboration between plumbing engineers and those with knowledge of the systems they interact with or depend on. In a commercial building or large-scale residential project, this team often includes a Mechanical, Electrical and Plumbing (MEP) firm, an architect, civil engineer, and structural engineer because of the complexity and interdependence with other systems. The architect starts with their understanding of the building needs and any additional jurisdictional requirements or governing documents, such as the International Building Code (ICC, 2018a). If using the IBC, the architect uses the occupancy type and the number of occupants to design the layout of the fixtures and appliances in the building for the supply side design. The model codes provide look-up tables for commercial or large-scale residential buildings to support this process. The project-specific requirements may exceed code requirements by providing additional fixtures. A piping diagram is created using design software or by hand to detail the plumbing serving each fixture and appliance. The pipe sizing requirements are based on flow rate and velocity limitations calculated using the IBC, the IPC, or the UPC, depending on which code is adopted by the local jurisdiction. The codes contain multiple sizing methods based on velocity limitations in the water supply, however the mechanical engineer may also need to consider acoustic requirements and the effects (e.g., corrosion and erosion) of water quality on the system.

The sizing method for the supply-side involves determining the available pressure on the site as well as the required pressure for the building and its plumbing fixtures. The plumbing engineer then must calculate the water supply demand for the entire building, for example using Hunter's Curve to predict peak demand load (See Textbox). Next, pressure losses through the building supply system are calculated, and the 'longest developed pipe length' and the most hydraulically remote fixture are estimated taking into account equivalent overall pipe length, pressure losses from fittings and changes in elevation. Next, the allowable friction loss for the entire system must be determined. The designer calculates the allowable friction loss per 100 ft of pipe by multiplying the building pressure after all losses and the required pressure at the most hydraulically remote fixture by 100 and dividing that by the length of the longest developed pipe length. The conservative nature of Hunter's Curves results in oversized pipes with lower friction losses. However, if the supply pressure is too low, a pump may be necessary. Finally, the designer must look up pipe size and flow requirements using charts in the plumbing codes that provide the correlation between pipe size, velocity, flow, and friction loss per 100 ft of pipe (specific to the selected pipe material) and finalize the pipe sizing for each element, based on the total water supply fixture units and the piping. There are separate demand vs. friction loss curves for hot and cold water supplies, which are used to determine the pipe size for each pipe segment.

The drain-side must also be properly sized to remove wastewater from the point of use at the fixtures to the discharge into the public sewers, as discussed in Chapter 14 of WHO (2006)). In gravity-fed systems, the horizontal drainage pipe from plumbing fixtures are connected to vertical drain stacks to transport the waste and sewage. Codes dictate numerous requirements including the materials and the minimum slope of the drain lines, depending on the size of the drainage pipe. Similar to the supply side, each fixture type in the building has an associated Drainage Fixture Unit (DFU) that designates the load and the associated trap size. The design of the drain system must provide for venting the drain traps to prevent the water trap seal from being compromised. In the case of buildings over 10 stories high, relief vents are used to equalize the pressure in the drainage stack. In the case of plumbing fixtures located below ground, the drain should be pumped up to a point above the ground level to prevent back siphonage of sewage. The sizing method for drainage and venting systems in buildings involves calculating the total number of DFUs for each sanitary branch and using those values to determine the required sizing for the sanitary branch. The main building drain is sized using the total of all DFU values and the vents using look-up tables and the DFU values.

For small residential plumbing design, the same general procedures are followed to size supply and drainage pipes, but the systems are typically much simpler with a main stack and fixtures within a short run of the stack. The design is often done by a mechanical engineer in coordination with the project architect. The International Residential Code includes building, plumbing, mechanical, fuel gas and electrical requirements for one- and two-family dwellings and townhouses up to three stories, including look-up tables that are specific to residential plumbing design (ICC, 2018c).

If a designer believes the system is oversized and would like to make a change, they apply for an exception from the code official, which is considered on a case-by-case basis. It is important to note in the context of the current report that existing prescriptive codes do not yet fully address the use of low-flow fixtures. For example, a plumbing code may specify hot water circulation be maintained at the target temperature at a location 20 feet of pipe ahead of a fixture, but for low-flow fixtures, water supplied to the occupant would not get hot enough without numerous and consistent hot water draws. Furthermore, on the drain side, there is a need to evaluate how the lower flow rates may impact the ability of the effluent water to adequately carry away debris.

In 1940, Roy Hunter, a researcher at the National Bureau of Standards, introduced a probabilistic method of estimating water demands. From limited actual building usage patterns, data, and extended laboratory research, Hunter presented the load producing values of different types of plumbing fixtures and from that developed curves that estimate the number of fixtures most likely to be operating simultaneously as a function of the total number of fixtures in the design. This determination established the necessary piping requirements for both supply and discharge. When employing the figures below, the designer will enter the Hunter curves from the x-axis, which lists the total fixture units. The designer then goes up the Y-axis to the curve that best fits the application. Because technology and design practices have changed since the development of Hunter's Curve, the results tend to oversize water supply piping systems, particularly when low-flow fixtures are used. Hunter's approach using the fixture unit was a means to simplify the computational analysis requirements. Recent increases in computational capacities have provided the means to apply a more complete and representative analysis. Modified Hunter's Curves have the potential to reduce both initial costs and operating costs by providing a more accurate estimation of demand in a building. (Galowin, 2008)

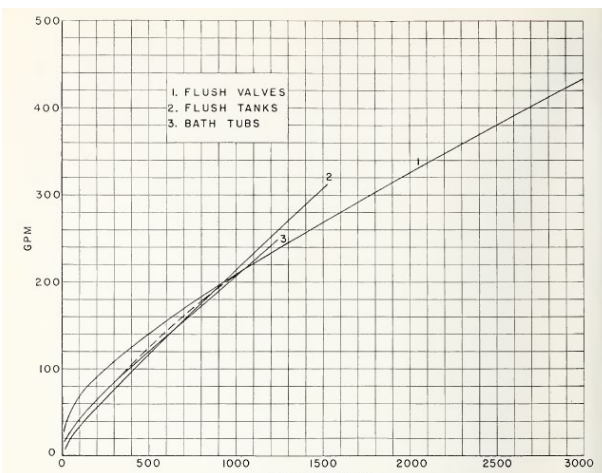

FIGURE 4.—Relation of demand to fixture units.

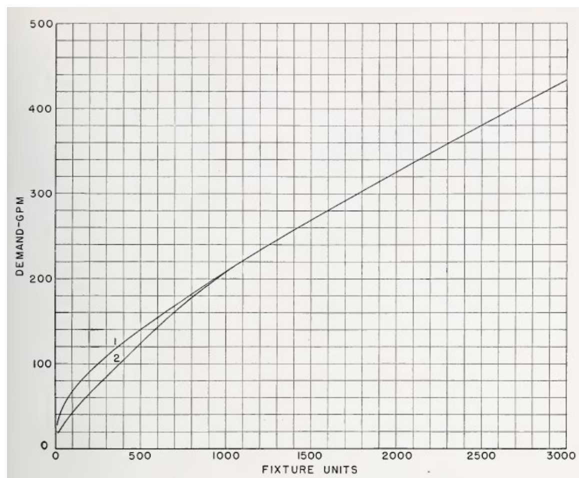

FIGURE 5.—Estimate curve for design purposes.

Original figures from Hunter (1940)

Design and Analysis Tools

Several software tools are available to researchers and practitioners for the design and analysis of premise plumbing systems. They include plumbing layout design tools, cost estimators and materials list generators; software that ensures code compliance of a design; and, pipe-network hydraulics simulation tools, computational fluid dynamics (CFD) software, and long-term water quality simulation tools. These tools are described in a table in Appendix C of this report, where they have been separated into Design tools in the first portion of that table and Analysis tools in the second portion. Design tools are used to layout drinking water distribution networks (from utilities to buildings) and premise plumbing systems and to assess these layouts for hydraulic performance and pump, reservoir, tanks, and sampling requirements. Analysis tools allow users to simulate detailed flow and pressure dynamics in systems as well as the transport and reaction of disinfectants and contaminants within them.

Of particular interest among these tools is the free, open-source EPANET water distribution system simulation software. EPANET was created in the early 1990’s in response to the water utility industry’s need for a model that integrated both hydraulic analysis and water quality modelling into one package. This software provided the basis for most of the proprietary and non-proprietary water quality models used today (Clark, 2015b). EPANET models hydraulic behavior and water quality within drinking water distribution systems, and has been used in a variety of research studies around the world (Clark, 2015a; Grayman, 2018). Using EPANET, one can run extended-period simulations of pipe networks and, for example, track the flow of water in each pipe, the pressure at each node, the height of the water in each tank, and chemical concentration, water age and source tracing throughout the network. The EPA released extensions that work with the base software to: (1) model complex reactions between multiple chemical and biological species in the bulk flow and at the pipe wall (EPANET-MSX) and (2) perform real-time pipe network simulations (EPANET-RTX). Software downloads and further details are available on the EPANET website https://www.epa.gov/water-research/epanet.

In 2011, IAPMO and ASPE convened a group to revise the methodology for properly estimating premise water supply demands in response to the increased use of water-conserving plumbing fixtures, fixture fittings and appliances, and the subsequent decreased demand for water in commercial buildings and residences. They sought to develop a statistically based probability model that would predict the peak water demand for single and multi-family dwellings having water-conserving plumbing fixtures. This model would be used to predict the peak water demand for the building supply and principal branches and risers of a residential plumbing system. This work led to the development of the Water Demand Calculator, which provides computational methods for estimating water supply demand for single and multi-family dwellings based on data from a recent study of residential buildings (Buchberger, et al., 2017). This calculator, which is incorporated into the IAPMO Uniform Plumbing Code (IAPMO, 2018b) and the IAPMO WE•Stand standard, is an Excel spreadsheet that was developed to avoid over-design resulting from the Hunter's Curve (IAPMO, 2017).

Premise Plumbing Modeling Studies

EPANET has increasingly been used by researchers to model hydraulics and water quality in pipe networks inside buildings. Abd-Elaal and Gad (2018) modeled alternative premise plumbing layouts to compare looped pipe networks with different pipe diameters and flow velocities to traditional, open-loop, branched networks inside buildings. Their objective was to assess hydraulic reliability of the designs (i.e., determine failure points, resilience under pressure, and minimum pressure required to supply required water). They found that looped configurations saved more in terms of cost and required system pressure. Researchers have also modeled disinfectant residuals, as in the case of Monteiro, et al. (2014), who used EPANET with the Multispecies Extension to simulate the second order decay of chlorine within drinking water systems. Disinfectant residuals decrease and disinfectant by-products increase the longer water stays in premise plumbing pipes. Thus, high water age can be linked to poor water quality and higher instances of plumbing pathogen regrowth. Schück (2018) used EPANET to simulate various premise plumbing designs within a building using either a tank-type or an instantaneous water heater and a stochastic demand generation model. Schück found that water age depended primarily on the usage pattern at the fixtures, that water age at the end of fixture "stubs" could be almost 2.4 times higher than the water at trunk branch points, and that average water age can be reduced by about 50 % when an instantaneous water heater is employed. Woo, et al. (2018) used an EPANET model to investigate metal transport by simulating axial dispersion within pipe networks and compared their results to lead measurements in pilot-scale plumbing systems. Woo et al. contend that given the intermittent nature of water use in buildings and the low flow associated with end uses such as dishwashers, ice machines, and water lines in refrigerators, modeling flow in premise plumbing systems needs to consider axial dispersion. Calculated dimensionless dispersion coefficients for simulations under a wide range of Reynolds numbers showed good agreement to those from pilot studies.

Modeling drinking water temperature within premise plumbing systems has received limited attention despite the important role of temperature on the associated physical, chemical and biological processes. Omaghomi and Buchberger (2018) compared the thermal performance of two plumbing designs for a 2-bathroom residential unit – one that is a traditional plumbing design and another that was appropriately sized for a water-efficient design with low-use fixtures. Using EPANET's first-order decay function, normally used to model chlorine residual, the authors simulated the cooling of hot water in copper pipes. Results suggested that a 30 % energy savings with respect to hot water use was possible with the right-sized plumbing layout.

Researchers at the KWR Watercycle Research Institute in the Netherlands modeled the temporal temperature variations at fixture end uses in a premise plumbing system using EPANET linked to a temperature model (using the EPANET-MSX extension) and stochastic water use demand models (Blokker and Pieterse-Quirijns, 2013; Moerman, et al., 2014; Zlatanovic, et al., 2017). They found good agreement when validating the model using data from comparable experiments. A sensitivity analysis determined that the most relevant parameters impacting the piping outlet temperatures were the inlet water temperature, the air temperature surrounding the pipes, and the thermal conductivity of the air. Zlatanovic et al. found that achieving convergence for the temperature model was challenging, given that the time scales for the simulation were at times not long enough to model the transient phenomena in premise plumbing, i.e., EPANET was designed and is better suited to model outdoor distribution systems.

Existing Research Facilities

In the 1970's, the drive to develop performance standards and to foster international collaboration in plumbing research led to the construction of plumbing research facilities. In 1972, the National Bureau of Standards erected a 5-story plumbing tower in Gaithersburg, Maryland to study the performance of plumbing fixtures, as well as water supply, drainage and venting issues (Wright, 2003). The tower was used intermittently into the 1980s for plumbing related research and was decommissioned in 2005. Also in the early 1970s, American Standard Inc., erected an 11-story vertical water-pressure testing facility at Stevens Institute of Technology in Hoboken, New Jersey. Plumbing research was carried out in this facility from 1972 to the late 1980s, and the building was demolished in 2009.

In 1976, a review of existing facilities outside the U.S. by Hanslin, et al. (1979) identified six plumbing tower facilities in Europe, ranging from 3 stories to 45 stories, as well as a tower in South Africa, documenting the organizations that sponsored the laboratories, the tower heights, and the research conducted there.

There are many research facilities currently in existence that are being used to study premise plumbing issues, as well as broader questions related to water distribution. The Facilities Accelerating Science & Technology (FAST) Water Network (https://www.waterrf.org/fast-water-network) connects researchers, new technology providers, and other innovators in the water resource recovery industry with test facilities at various scales starting from research laboratories (bench scale) to R&D/piloting facilities (utility scale). With input gathered by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), the Water Research Foundation (WRF), the Water Environment Federations (WEF) and the National Science Foundation, this network assists in developing and piloting technology to help manage risk and accelerate the adoption of wastewater technology innovation. While FAST is currently focused on wastewater testing, it could be expanded to include other plumbing and water distribution testing facilities.

In addition, there are zero- or low-energy research homes where water use issues are also being studied. In 2012, NIST built the Net-Zero Energy Residential Test Facility (NZERTF) in Gaithersburg, MD for evaluating renewable and energy efficient building systems. With regards to water use, the home has energy and water efficient appliances and fixtures, and a PEX-manifold "home-run" plumbing system. Studies are being conducted on thermal losses from plumbing (Ullah and Healy, 2016), thermal performance of water heating systems (Ullah and Healy, 2016; Balke, et al., 2016), and premise plumbing microbial and chemical water quality. More information about the NZERTF, including recent publications and research results, can be found at https://www.nist.gov/el/net-zero-energy-residential-test-facility.

Whirlpool Corporation and Purdue University transformed an existing 1920's home in West Lafayette, IN into a research facility called the Retrofit Net-zero: Energy, Water, and Waste (ReNEWW) house (https://www.whirlpoolcorp.com/reneww-house/). The ReNEWW house is used to study how retrofit homes can be models of sustainable living, incorporating deep energy efficiency upgrades to the building envelope, new appliances, water efficient plumbing, a greywater treatment system, rainwater collection, hybrid photovoltaic thermal solar collectors, and a geothermal HVAC system. After retrofits, ReNEWW residents consumed only 80 L

(21 gal) per person per day (a 75 % reduction as compared to pre-retrofit water use). The Purdue University Center of Plumbing Safety has recently published studies on corrosion of upstream metal plumbing components impacting downstream PEX (cross-linked polyethylene) pipe (Huang, et al., 2019), premise plumbing hydraulics-water quality models (Lee and Whelton, 2018) and water use and water quality in the ReNEWW house (Salehi, et al., 2018). The ReNEWW house, as well as other facilities, are also being used in a larger study being funded by the U.S. EPA as described in the next section.

Current Research Efforts

In 2016, EPA's Office of Research and Development issued a Request for Applications to pursue research into issues of water quality related to distribution and premise plumbing systems (https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.rfatext/rfa_id/613). Based on findings from a National Research Council (NRC) report mentioned earlier (National Research Council, 2006), which states that a substantial portion of the nation's waterborne disease outbreaks are attributable to premise plumbing water quality issues, EPA concluded that the issues were of national scope and high priority. Proposals were sought to conduct research on water conservation trends and the effect of water flow on water quality, and to use that information to develop web-based decision support tools that assist in "right-sizing," materials selection, pipe network design, and determining sampling port locations for plumbing systems in various building types. This request was very much in line with the motivations for the research needs identified in the current document.

EPA funded two projects that are currently underway. The first project, entitled *Water Conservation and Water Quality: Understanding the Impacts of New Technologies and New Operational Strategies* was awarded to a team led by Drexel University in Philadelphia, PA and includes ESPRI (the Environmental Science, Policy, and Research Institute) and the University of Colorado at Boulder. These projects are ongoing. This project consists of several tasks: interviewing subject matter experts and facility managers, and reviewing existing guidance documents to identify areas of consensus, priority concerns and knowledge gaps to support the development of a decision support tool; developing guidance values for the concentrations of opportunistic pathogens and disinfectant residuals; developing a model for residence times in plumbing systems; and, conducting an experimental program in pipe rack and water heater laboratory setups to investigate the effects of pipe material, diameter, use, and disinfectant approach on the levels of opportunistic pathogens. Separate pipe rack facilities have been established in Philadelphia and Boulder in recognition of the use of chloramine and free chlorine disinfection at the two locations, respectively.

The second project, entitled *Right Sizing Tomorrow's Water Systems for Efficiency, Sustainability, and Public Health*, was awarded to a team led by Purdue University in West Lafayette, IN and involves researchers from Michigan State University, San Jose State University, Manhattan College, Tulane University and the University of Memphis. The project goal is to better understand and predict water quality and health risks posed by declining water usage and low flows. Among the project objectives are to improve the public's understanding of decreased flow to elucidate the factors and their interactions that affect water quality through fate and transport simulation models for residential and commercial buildings, and to create a risk-based decision support tool to help guide decision makers through the identification of premise plumbing characteristics, O&M practices that minimize health risks to building inhabitants. In addition to the ReNEWW house at Purdue, this project includes water quality experiments in several educational buildings and a laboratory setup that is similar to the pipe racks in Philadelphia and Boulder. This research effort is still in progress, with results expected soon.

WRF (https://www.waterrf.org/our-mission) has a major role in coordinating and funding "… research in the technology, operation, and management of water, wastewater, reuse and stormwater collection, treatment and supply systems, towards ensuring water quality and improving water service to the public." Some of the research projects they have funded and continue to fund address fundamental questions regarding water efficiency and water quality impacts on premise plumbing that are consistent with the scope of the current effort as follows:

> Project #4619: *Developing Water Use Metrics for the Commercial and Institutional Sectors,* completed in late 2019 explored factors affecting water demand in the non-residential buildings, specifically: lodging, office buildings, schools/colleges, health care facilities, restaurants, retail stores, warehouses, auto services, religious buildings, and nursing homes. Project leaders analyzed water use for over 18000 buildings and laid out an approach for utilities to set benchmarks for promoting efficiency with their customers (Fedak, et al., 2019; Volckens, et al., 2019).
>
> Project #4689: *Assessing Water Demand Patterns to Improve Sizing of Water Meters and Service Lines* addressed a common problem for utilities regarding water meters that are oversized because of the increasing implementation of water conservation and low water-use plumbing fixtures (Mayer, et al., 2020). The project investigated peak and off-peak water demand patterns of typical, non-single-family urban water customers to more accurately and economically size water service lines and water meters.
>
> Project #4721: *Detecting and Differentiating Opportunistic Premise Plumbing Pathogens to Determine Efficacy of Control and Treatment Technologies* aims to develop a unified methodology for accurately detecting and quantifying bacterial and protozoan OPPPs in drinking water systems, with a particular focus on the four that present the greatest health risk: *L. pneumophila*, *P. aeruginosa*, nontuberculous mycobacteria, and *Acanthamoeba spp*. The team is also examining the effectiveness of OPPP mitigation strategies with a focus on in-home premise plumbing modifications.
>
> Project #4911: *Sampling and Monitoring Strategies for Opportunistic Pathogens in Drinking Water Distribution Systems* seeks to develop sampling and detection methodologies for OPPPs to understand their presence in bulk water, biofilms, and sediments in drinking water distribution systems before they enter premise plumbing systems.
>
> WRF recently funded Project #5033: *Demonstrating the Effectiveness of Flushing for Reducing the Levels of Legionella in Service Lines and Premise Plumbing* to evaluate the use of water quality parameters as indicators of the effectiveness of flushing and to develop data-driven flushing guidance for *Legionella* control.

This section on Background and the previous Introduction describe how the building and plumbing communities have pursued and are continuing to pursue lower water use and improved water quality. To make the transition toward lower water consumption, the parties involved in designing and operating plumbing systems first need to have a thorough understanding of water demand in buildings: How much water is used in buildings, and how is it used? What are the requirements for both the quantity and quality of water to safely and dependably provide the desired functions? In light of reducing water use, what is the technology needed to achieve reductions in water use, as well as the impacts those reductions have on the rest of the premise plumbing system, the distribution network, and the drainage and waste systems? Furthermore, because of the increasing interest in using alternative sources of water for non-potable applications to achieve even higher levels of efficiency, what impacts will shifting this demand to alternative sources have on the remaining plumbing network? The research needs identified in the following section are intended to address those questions and more in the pursuit of lower water use and higher levels of water quality.

RESEARCH NEEDS

Tables 1 and 2 describe the individual premise plumbing research needs identified in this effort. They have been developed based on the research priorities from the August 2018 workshop held at NIST, responses to the Federal Register Notice (FRN) issued in October 2018, and additional information collected by NIST from various stakeholders and through other NIST investigations. These tables are formatted as follows: An overarching research area (designated with a letter and number, e.g. F1, **in bold font**) is presented followed by a brief description. Individual research topics are listed under each area (***in bold italics***), with a short description along with relevant references if any exist. These references include the research priority number from the August 2018 NIST/EPA/WRF workshop report (Pickering, et al., 2018) if applicable, or a letter designation if it was submitted in response to the FRN. In other cases, the topic is noted with NAS if it came from the National Academies report on *Legionella* (National Academies of Sciences, 2019), WRF if coming from a research report of the Water Research Foundation, or another reference as appropriate. Table 1 is focused on Foundational Measurement Science research such as performance metrics and predictive models, while Table 2 includes Applied Research topics such as design methods and O&M issues.

Table 1 Foundational Measurement Science

Area #F1: Terminology	
A number of terms are widely, but inconsistently, used in the premise plumbing field. To support future research efforts, and ultimately the development of updated design methods, standards and guidelines, a shared language is essential for clear and productive discussions.	
Standardized definitions of key terms	Workshop - 14
Several terms common to the field of premise plumbing, including even fitting and piping, are not used consistently and need to be more precisely defined. In addition, the Plumbing Industry Leadership Coalition (PILC) has reached out to the US EPA noting the need for definitions of terms related to water re-use, including graywater and blackwater. While not a traditional research project, the development of rigorous definitions is needed to provide a shared language in support of future research, standards development and other activities. Standardized terminology could be developed under an existing Standards Development Organization (SDO) or using an ad hoc group or workshop that would then publish a guidance document containing these definitions.	
Taxonomy of plumbing system design and layout	FRN - T
In addition to developing accepted definitions of "plumbing system" and "premise plumbing," there is also a need for a standard approach or taxonomy for describing system layout and key design elements (e.g., water volumes, dead-ends, stagnation points). Such a taxonomy would support the consistent description of systems and would be coupled with a protocol to characterize plumbing system layouts. It would also support future research, standards development and other activities, and could be developed by an existing SDO or using an ad hoc group or workshop.	
Potential products for Area #F1 Terminology: • Technical report of draft terminology and definitions • Consensus standard or guideline on premise plumbing terminology • Taxonomy for describing plumbing system layouts • Protocol for characterizing premise plumbing system layouts • Consensus standard or guideline for characterizing and describing plumbing system layouts	

Area #F2: Metrics	
To characterize water quality and efficiency in premise plumbing systems, standardized metrics need to be established with common definitions that are accepted by all stakeholders. Performance factors for which such metrics are needed include flow characteristics (e.g., velocity, volumetric flow, pressures), water quality characteristics (chemical and biological), and other system descriptors (e.g., water residence time, time scales, piping material characteristics). Once these metrics are standardized, it will be more straightforward to develop test procedures and assessment techniques to provide information on plumbing system performance.	
Metrics for long-term durability and resilience	Workshop - 17
There is a need for shared definitions of the important aspects of plumbing system durability and resilience that capture the relevant performance factors and time scales. These definitions and metrics will provide a fundamental building block for system design and performance to support other research topics and design guidance.	
Chemical and biological attributes of influent water	Workshop - 30, FRN - M
The condition of the water entering a building is a critical factor in understanding and assessing water quality in premise plumbing systems. Metrics that describe the chemical and biological attributes of the influent water, including stability, will inform effective system management practices.	
Chemical and biological attributes of wastewater	Workshop – 21, 24
The condition of wastewater plays an important role in the resiliency of the materials used to construct waste conveyance systems, and we need to better understand the chemical and biological contents of the water as they impact these systems. As buildings move towards lower flows and incorporate onsite collection and water reuse strategies, the concentrations of chemical and biological contaminants on the drainage side of the system may increase. Also, new technologies and materials incorporated in plumbing systems will impact the water quality in the drainage system.	
Water quality targets specific to facility type	FRN - U
There are currently limited regulations and codes with requirements for indoor water quality, testing, and treatment for different types of facilities. Metrics for water quality are critical to meet the unique needs of different facilities, account for the population served, types of piping, geographic location, and other features. For example, the healthcare industry is increasingly adopting internal water management systems as essential tools for protecting the health and safety of patients, and their requirements are not likely to be the same in other types of facilities.	
Metadata development	Workshop - 18, 43
Standard metrics, classes and subclasses are needed to describe buildings and building characteristics including location, age, occupancy and activities in a consistent manner. These metadata are key to the development of databases of plumbing system performance and water usage so that the relevant features of the buildings associated with these data are clear.	
Potential products for Area #F2 Metrics • Technical report describing metrics and key performance factors, including system durability and resilience and influent and wastewater chemical and biological characteristics • Consensus standard or guideline defining metrics and key performance attributes • Candidate water quality targets for different types of facilities, leading to consensus standards and guidelines to meet these targets • Technical report describing building metadata for plumbing system performance characterization, leading to consensus standards and guidelines	

Area #F3: Data	
Data are needed to understand water use and premise plumbing conditions to establish a sound baseline for existing system designs and performance. These data are also needed to inform changes in plumbing codes and standards, to compare the performance of new system designs, and to evaluate trends over time. Building types covered need to include single-family homes, multi-family buildings, commercial buildings, mixed-use buildings, institutional buildings, schools, daycare facilities, hospitals, assisted living facilities, and multi-building campuses.	
Data on water demand patterns for various building types	Workshop - 2, 6, 17, 18, 32, 44 FRN - A, E, K
Field surveys of water usage in buildings are needed to acquire representative data in a variety of commercial, residential, and institutional buildings as well as multi-building campuses. High-accuracy and high-resolution data are needed for a wide variety of building types (i.e., single-family, multi-family, commercial, mixed-use, hospitals, schools, daycare, assisted living, institutional, and multi-building campuses). The data need to include distributions of: daily water usage; service line length and diameter; length and diameter of hot- and cold-water piping in buildings; incoming water pressure; hot water temperature at taps; and residence time at each branch of the plumbing system. Granular data at individual POU will support detailed understanding of performance and support effective reductions in water consumption. Demand data will also be useful for examining how demand impacts water quality within plumbing systems. These data will be especially helpful in understanding how vulnerable populations (e.g., occupants in hospitals, healthcare, daycare, and assisted living) might be affected by the presence of OPPPs. The use of continuous, real-time monitoring throughout plumbing systems will be particularly helpful.	
Water use data to update Hunter's Curves	Workshop - 3, FRN - N, O
Water use data are needed to develop and validate sizing models to replace Hunter's Curves to predict peak water demands based on the number of plumbing fixtures in a building, thereby improving minimum and maximum pipe sizing. These models will eventually be incorporated into updated plumbing codes to reflect current and future trends of lower water flow in buildings. In addition, sizing of water distribution piping (at utility and building scales) will be improved with these data.	
Water quality data at point of entry and point of use	FRN - C, P, U
Monitoring water at building POE and POU for disinfectant levels, OPPPs, perfluoroalkyl and polyfluoroalkyl substances (PFAS), microplastics, lead, and arsenic is needed to understand and evaluate the impact of building systems and plumbing designs on building water quality, including changes between POE and POU. Data on water treatment practices are also needed to characterize the scale of treatment and delivery for all types of buildings within public water systems. These data will also help inform water temperature management, efforts to reduce stagnation, and implementation of flushing protocols. These data would be most useful in a nationally-representative, building water use database to facilitate the benchmarking of existing and future buildings. Such a nationally-representative building dataset also has the potential for developing correlations between water usage and building size and type.	

Occupant behavior and preferences	Workshop - *2*
Field surveys, including interviews of building occupants, are needed to acquire representative data on how building occupants use water and maintain various system components. These studies should aim to understand the preferences driving these behaviors and how and why these behaviors and preferences have changed and may continue to change over time.	
Data on biofilm and scale development	Workshop - 4, 35, 41; FRN - Q, U, V; WRF 4379
New and innovative plumbing products and water efficiency efforts have drastically changed the way plumbing systems perform, with practice trending towards smaller diameter piping. Questions have been raised about the microbiological implications, and there is a pressing need to understand how factors (physical factors such as pressure and system age, and operational factors such as water age/stagnation, flow rate, water velocity, and water temperature) impact biofilms and scale and their impacts on water quality within different materials. These impacts include growth rates, types of biofilms, general biofilm characteristics, and ecology. Biofilms and scale are important because they are major drivers for water quality problems, e.g., biofilms can harbor pathogens and protect them from disinfectants. Scaling can reduce heat exchanger performance, degrade piping, and increase pathogens, but it can also have a protective role against lead by forming a barrier against erosion and corrosion. These data are needed to support system designs that reduce stagnation and locations where OPPPs are able to grow. Design strategies also need to minimize surface areas where biofilms can develop.	
Data on water conditions to support design and operation for OPPP control	Workshop - 27, 33, 36; FRN - C, D, F, O, N; WRF 4379; NAS
Research is needed to gather data on disinfectant levels, temperature, and microbial concentrations in plumbing systems to support system designs and operating strategies with reduced OPPP risks. Examining international approaches to design and operation that reduce reliance on disinfectants is important as well. This research would investigate the practical limits of low water use strategies (e.g., net zero water, rainwater harvesting, greywater recycling, etc.) and the feasibility of separate water distribution systems for potable applications. Electronic faucets and thermostatic mixing valves can harbor higher levels of OPPPs because they provide surfaces and temperatures that can promote biofilm growth. Research is needed to study whether and how these fixtures impact the prevalence of OPPPs at POU and the effectiveness of design approaches to minimize these impacts.	
Data quantifying system impacts on dissipation of chlorine and other disinfectants	Workshop - 7; NAS
Residual disinfectant is a primary controller of water quality, and there is a need to study the impacts of system design on the dissipation rate of chlorine or other disinfectants. Such system factors include: water age, flow rate, and velocity; water temperature; water pressure and its variation; plumbing materials; water source; in-house treatment at both POE and POU; operation and maintenance; and, plumbing layouts (trunk and branch or in series).	
Data on the effects of residence time on scaling and water quality	Workshop - 7, 11, 16; FRN - B, D, S
Data are needed on the effects of residence times on scaling and water quality due in part to the relationship between scaling and water quality. Information is needed on the design parameters that affect residence time and the economic implications of different design approaches for managing residence time and scaling. This information will be useful to support the development of design guidance for practitioners. Given that water can sit in a system for weeks at a time in some low-water use buildings, guidance is needed to address this specific situation.	
System design information following disease outbreaks	FRN - L
Following plumbing pathogen disease outbreaks, field data must be taken to document plumbing system layouts, fixtures, equipment types and configurations, stagnation points, and excess storage to understand their impacts on the risk of pathogen growth and transmission.	

Potential products for Area #F3 Data:

- Nationally-representative databases of water use and water quality for commercial, residential, and institutional buildings, including:
    - Water use data to validate updated sizing models
    - Water quality data at POE and POU
- Research studies on how system factors, including residence time, influence biofilms and scaling, impact water quality
- Research studies on the impacts of design on the dissipation of chlorine and other disinfectants
- Research studies on the impacts of system design and water conditions on OPPPs
- Research studies of how building occupants use water that provides an understanding of their preferences and how these preference may change over time
- Plumbing system design information from disease outbreaks
- Design guidance to address system residence times, particularly in low water use buildings

Area #F4: Flow and Transport Fundamentals	
There are important knowledge gaps regarding flow and transport dynamics in premise plumbing. A better understanding of the physics, chemistry, and biology related to plumbing systems is needed to design, install, operate and maintain these systems in a healthy, efficient, and sustainable manner.	
Hydrodynamic flow regimes and transport	Workshop -20, 23
For the piping sizes and flow rates that are common in practice, the variation in Reynolds number can be large enough to transition from laminar to turbulent flow in different portions of the same network. This phenomenon makes it very difficult to estimate pressure drop, which is needed to design plumbing systems. Also, because of the nature of the different flow regimes, they also influence the way that water flowing through the piping network transports treatment chemicals and biota. The details of flow and transport are of particular importance in hot water lines, where the water in the piping network far from the water heater may be significantly colder than near the heater. This is important because the thermophysical properties of water can vary significantly with temperature; in particular, the dynamic viscosity of the colder water can be as much as twice that of the hot water.	
Pressure losses as a function of materials and fitting geometry	Workshop -20; FRN - N
Pressure drops as a function of flow rate for plumbing fittings and components are not well characterized, making it difficult to understand flow dynamics and to design systems. Standard methods of test are needed to characterize these pressure-flow relationships. The lack of reliable data exists in part because internal diameters, turn radii, length of straight sections entering and exiting, and diameter transitions are determined by the manufacturing processes used to make these fittings and components. Current products characterized by the same size and function can have vastly different pressure drops for a given flow rate, sometimes varying by orders of magnitude. These pressure drops can also vary significantly with the manner in which these products are installed.	
Chemical processes in plumbing systems	Workshop - 1, 7, 47, FRN - Q, U, NAS
Chemical reactions occur inside piping networks, in part because of disinfectants, usually chlorine based, used in the water to control biological hazards. These chemicals can react with substances present in piping in ways that can produce hazardous by-products. Also, chemicals used in piping components can diffuse into the water. Material age is also likely to play a role given that older systems are more corroded and have thicker layers of deposited materials, with rougher and more pitted surfaces that can be preferential sites for reactions. These reaction mechanisms need to be understood to support guidance for design, operation, and maintenance.	
Biological processes in plumbing systems	Workshop - 1, 4, 25, 38 FRN - B, D, F, H, N, Q, U, Y; WRF 4379
The microbial ecology within plumbing networks can be complex and needs to be better understood. Rust, bacteria, and microbes will, over time, deposit and stick to the inner walls of the piping network. These biofilms can provide a nutrient rich anchor point for pathogens to grow. There are several factors that influence pathogen growth, including the amount of time water remains stagnant in the pipes, flow rates, temperature, and piping materials. Understanding of these processes is needed to manage microbial conditions and otherwise protect these systems.	
Plumbing material leaching	FRN - J; WRF 4379
Materials used to manufacture plumbing system components can leach into water over time and react with water treatment chemicals. Contamination of water with these chemicals and materials in piping and fittings can be problematic, with lead being of high concern due to its known health effects. Better understanding of the leaching of lead and other chemicals into water systems is needed. Improved standards are also needed for certifying "lead-free" or "non-lead-leaching" pipes, fittings, and fixtures.	

Material and chemical impacts on biofilms, pathogens and scaling	Workshop 1, 5, 47; FRN - D, K; WRF 4379
Research is needed on the links between water quality at different points within plumbing systems and biofilm formation, pathogen growth and scaling. This research needs to specifically address changes in water quality and treatment chemical concentrations throughout the system due to interactions with piping materials and other processes.	
Impacts of residence time on water quality	Workshop 1, 5, 47; FRN - G, L, U
It is well known that water quality is influenced by the age of the water in the plumbing system. Disinfectants added to the water at the treatment facility are consumed over time and diminish their ability to suppress pathogen growth. The physical arrangement of a plumbing system affects residence time, because the water flow rate is inversely proportional to the residence time. Also, lower flows reduce the amount of shear on the inner pipe walls, which can facilitate biofilm growth, and higher residence times provide more opportunity for reactions between the water and piping materials. For these reasons, it is important to understand the relationship between system designs and residence time and the resultant impact on water quality	
Impacts of water source on water quality	Workshop 1, 5, 47
Different water sources will contain different chemicals and biologicals and will vary in other respects, such as pH level. These factors influence the manner in which water must be treated, and therefore the chemistry and by-products of such treatment will be different. A better understanding is needed of how different water sources influence water quality.	
Impacts of reduced flow rates on drainage systems	Workshop 21
Water efficiency efforts have reduced water flows in drainage systems, raising questions related to minimum acceptable flow rates to ensure proper flow, drainage, and the movement of solids. This information is needed to design systems that operate effectively at both minimum and peak flows.	
Improved venting requirements based on modern system demands	RFI - N
Venting systems provide the volume of air needed to balance pressure transients occurring in plumbing systems to protect trap seals. Modern toilets have lower and varying discharge rates with short surge flows that do not affect the pressure equilibrium as severely as predicted in the design tables, which are based on data published more than 75 years ago. Updated venting requirements are needed for drainage systems with low discharge fixtures.	

Potential products for Area #F4 Flow and Transport Fundamentals:

- Improved understanding, data and models of water flow in plumbing and wastewater systems
- Detailed hydrodynamic models of water flow in plumbing systems
- Methods of test to measure pressure drop through plumbing fittings and components
- Improved understanding of chemical and biological processes in plumbing systems, including the effects of materials, disinfectant levels, water flow and other system parameters
- Improved models of chemical and biological processes in plumbing systems
- Better methods to measure material leaching into water from plumbing system components and models to predict these processes
- Technical data characterizing scale formation and biofilm and bacterial growth rates in piping networks, including characterization of microbial nutrients, chlorine residual decay, temperature, flow rate, residence time, materials, system age, and other relevant issues
- Models to predict scale formation and biofilm and bacterial growth in plumbing systems
- Data on the impact of water sources on water quality in plumbing systems
- Data to support updated vent sizing requirements in drainage systems

Area #F5: Measurement Methods	
Standardized methods are needed to collect data on premise plumbing systems both in the field and in the laboratory. The need for methods to measure pressure/flow characteristics of plumbing fittings was mentioned under #F4, but this research area is broader in terms of the parameters for which measurement methods and test procedures need to be established. These methods are critical to pursuing many of the research needs identified in this effort.	
Methods to collect end-use data	Workshop - 9; FRN - X, Y
A research need was identified under #F3 to better understand water use in buildings based on field surveys in a range of building types. Prior to embarking on such a study, however, methods need to be established to identify the parameters to be monitored, the approaches to accurately collect these data, including the measurement frequency; the duration and location of monitoring; and data reporting requirements and formats.	
Test methods for water quality in supply and distribution systems	FRN - K, P, U
Improved methods for measuring and monitoring water quality in plumbing systems are needed, including continuous, real-time monitoring of POE and POU water quality parameters such as conductivity, disinfectant residual, turbidity and contaminants levels. These test methods need to account for the fact that different facilities have unique system designs and water quality needs depending on the population served, type of piping, geographic location, and other features. These methods need to be developed to enable alarms to alert building owners/managers when incoming water departs from required quality limits and when POU conditions depart from target values.	
Performance of fittings and pipes	Workshop - 14, 20
Many new types of fittings, pipes, and joining methods are being introduced, and there is a need to understand the flow versus pressure characteristics and other performance parameters under different operating conditions. There is a lack of established test procedures to define standardized ratings of performance that can be independently validated. Test methods and metrics are also needed to characterize pressure drops through plumbing features at different flow rates and temperatures.	
Protocol to describe plumbing design of existing buildings	Workshop - 40
In assessing water quality and water use in existing buildings, which was identified under #F3 for improving premise plumbing systems, a standardized description of the plumbing systems that are present in the study buildings is needed. A protocol is also needed to identify characteristics that fully describe premise plumbing systems, and statistical methods are needed to survey existing buildings to collect representative data on those characteristics.	
Improved and less expensive meters	FRN - O, X
To better understand water use in buildings, water meters must be improved and installation and operation costs need to be reduced to enable collection of the data necessary for statistically valid datasets. The improvement of meters will also enable improved operations by allowing building owners/operators to identify opportunities for more efficient use of water and to detect faults in premise plumbing systems.	
Potential products for Area #F5 Measurement Methods • Test methods and protocols for conducting field surveys of water use and water quality in buildings • Test methods for characterizing the performance of fittings and pipes • Protocols to identify and describe plumbing system designs in existing buildings • Performance specifications for water meters • Prototype meters for improved and lower-cost real-time monitoring. • Guidelines on field data collection methods • Guidelines for the installation and use of continuous, real-time meters	

Area #F6: Model Development	
Reliable and accessible plumbing system models are needed to predict system performance and to investigate the impacts of different technologies and design approaches. Research is needed to develop the tools needed to improve existing models, develop new ones, and validate their predictions.	
Simulation tools of water flow, supply and drainage	Workshop - 13, 23, 45; FRN - A, I, O
Computer models of hydraulic behavior in plumbing systems and plumbing design tools can be improved to make more accurate predictions and to be easier to use in the design process. Integrating these tools with BIM platforms would enable more comprehensive building design approaches.	
Reference buildings and plumbing systems	
Reference buildings, similar to those that exist for building energy analysis, should be developed for the application of premise plumbing models and simulations tools to study the impacts of different technologies and design approaches. These buildings need to include commercial, institutional and residential buildings over ranges of size, geographical location, and building age to enable analyses of nationwide impacts of technologies and designs. Each building model should include plumbing systems relevant to the building type and the plumbing code in effect at the time of construction.	
Data to validate plumbing models	Workshop - 13
Detailed monitoring data of both hydraulic behavior and water quality are needed to validate existing and new plumbing system models. Full-scale tracer studies in hot and cold pipe in buildings would be a useful source of such data.	
Expansion of plumbing models to include thermal analysis	Workshop - 13, 26
Computer models used by engineers and consultants to simulate flow and chemical transport and reactions within premise plumbing systems need to incorporate thermal modeling to more accurately predict water quality in buildings. Many researchers use EPANET, a software application that models flow, reactions, and dispersion in water distribution systems, for modeling building premise plumbing. However, EPANET currently assumes isothermal conditions within the system, which limits its ability to capture important temperature impacts on chemical and biological processes. Adding thermal analysis capabilities would also improve the ability to study the energy implications of different technologies and design approaches, particularly on the hot water side of a system.	
Expansion of chemical and biological models	Workshop - 13; WRF 4383
Models of chemical and biological phenomena in water systems should continue to be improved, given that they currently implement incomplete treatments of chemical and biological processes. A risk-based exposure model for *Legionella* and other OPPPs would also be a useful addition.	
Models to estimate reduced drainage loads	RFI - N
Current drainage sizing tables are derived from estimating sewage loads using outdated methods. New probabilistic models are needed for estimating reduced drainage loads within buildings to properly size drainpipes. Since discharge volumes of plumbing fixtures have been reduced, it is expected that loading in drainage systems is also reduced. Also, reductions in the coincidence of overlapping discharges will further result in reduced pipe sizes.	
Potential products for Area #F6 Model Development • Improved algorithms and simulation programs to model water hydraulics, as well as chemical and biological processes in plumbing systems • Plumbing system design tools that integrate with BIM platforms • Reference building models, including plumbing systems, for use in simulating the impacts of different technologies and design approaches • Datasets for validating plumbing simulation model predictions of hydraulics and water quality • Addition of thermal analyses to plumbing system models • Enhancement of the chemical and biological capabilities of EPANET • New probabilistic models to estimate drainage loads	

Table 2 Applied Research

Area #A1: System Design Issues	
System design affects pressures, velocities, stagnation times, and temperatures throughout plumbing systems, which in turn affect water quality. Research is needed to improve system design to mitigate water quality problems and improve system performance.	
New plumbing system designs and technologies	Workshop - 19, 31; FRN - W
In response to the need to reduce water consumption, and in recognition of water quality concerns, new technologies and system designs are being developed, and in some cases implemented (e.g. mixing valves, POU and heat pump water heaters, combined hydronic/potable heating systems, grid-interactive water heaters and recirculation systems). While many of these new systems and components hold promise for achieving both water consumption and quality goals, questions exist regarding their actual performance, optimal design and installation, operation and maintenance, and other issues. Many of the research needs identified in this report are intended to address those questions. In addition, a technology assessment of these new technologies and design approaches is needed, including an analysis of trends that are likely to impact both research and practice.	
Validation of alternative sizing models and methodology for integration with plumbing codes	Workshop - 3, 11
Alternative sizing models (e.g., IAPMOs Water Demand Calculator) are needed to reflect current and future trends towards lower water flows. These models need to be validated and improved to establish minimum and maximum pipe sizing (based on data described under #F3). New methodologies, based on representative field data, would support code revisions.	
Potential side-effects of water and energy-efficient systems	Workshop - 10, 27; NAS
Water- and energy-efficient systems, and the technology, designs, and O&M strategies they tend to employ, are becoming more common and even being mandated in some areas. Research is needed to understand the impact of such systems on water quality and on how to design them to limit potential side effects. This research needs to include the influences and risks of design and operation approaches, including lower flows and reduced temperatures. Potential side effects of interest include noise, cavitation, water hammer, pressure surges, reduced water quality, increased erosion, biofilm growth, and scaling. This research could mitigate the unintended consequences of efficient systems and address the impacts of water heater temperature settings on water quality and energy use.	
Hot water plumbing design	Workshop - 26, 27; FRN - K, T, U; WRF 4379
Research is needed to understand temperature profiles (both spatial and temporal) in hot water distribution systems to guide temperature settings for water heaters. High temperature water is a critical line of defense against some OPPPs, particularly when residual disinfectant levels are not adequate. Given that energy efficiency objectives can motivate lower temperature settings, research is needed to better understand the relationship between energy efficiency and water quality in hot water systems. This research could involve thermal modelling of plumbing systems, including water heaters, potentially impacting how water heaters and distribution systems are designed.	
Multipurpose residential piping and sprinkler systems	Workshop - 42
Multipurpose residential piping and sprinkler systems can contain substantial amounts of stagnant water under conditions that provide breeding grounds for OPPPs. Research on the distribution, residence time, and temperature of water throughout these systems is needed to understand the associated risks and to develop options for reducing them. Findings will inform code requirements and design practice, particularly in residential fire sprinkler systems.	

Comparison of trunk-branch and series distribution systems	Workshop - 34; FRN - V
Research is needed to compare trunk-branch and series water distribution systems in terms of the occurrence of dead-ends, water distribution and residence times within the systems. This research should examine how unwanted dead-ends are arise during design or renovation. This research should also examine the presence or absence of two-step decontamination and disinfection and reversible flow, and how these approaches impact water quality.	
Impacts of alternative water use	Workshop - 12
Alternative water uses (i.e., net zero, rainwater harvesting, greywater recycling, on-site reuse) are being codified in some jurisdictions, and there is a need to understand their impacts on design, operation, and performance. Some of these approaches have the potential to increase stagnation as well as to impact conditions in sanitation systems. There is a need to understand the impacts of these alternative water uses on plumbing design and water use patterns for both potable water and wastewater before alternative systems are widely implemented.	
Impacts of design, reuse, reduced flows, materials, and water quality on wastewater systems	Workshop - 21, 24, 46; FRN - X
Research is needed to study how innovative products and piping designs impact minimum flow rates required to carry solids through drains, including run-out lengths and diameters and end-use flow rates. New technologies, materials, and upstream water quality products have been developed, but a full understanding of their impacts on wastewater systems is needed, including septic and public collection systems. Studies also need to consider whether reducing drainage system pipe size results in better removal under low flows and minimizes corrosion. At present, some drainage systems can effectively become septic systems due to longer residence times. Changes in wastewater concentrations can also impact materials. This work should build on previous research by PERC on commercial buildings with longer drain lines.	
Potential products for Area #A1 System Design Issues • Assessment of new plumbing technologies and design approaches, including trends in their development and application • Validated sizing methods for incorporation into plumbing codes • Technical data on temperature and other performance parameters in water- and energy-efficient plumbing systems, including information on potential side effects of temperature settings on water quality and materials • Technical data from comparison of traditional dead-end and closed-loop distribution systems • Technical data on the development of OPPPs in combined hydronic/potable systems • Technical data on impacts of new supply-side technologies on wastewater systems, including information to support pipe design guidance to ensure drainage performance • Technical assessment of alternative water systems, e.g., rainwater harvesting and on-site reuse • Design and installation guidance for water heaters and hot water distribution systems • Design strategies that reduce water use and minimize development of OPPPs • Design and installation guidance for alternative water systems	

Area #A2: Installation, Operation and Maintenance	
Based on results from the research needs identified earlier in this report, as well as other studies described under this area, best practices are needed to support improvements in installation, operation, and maintenance of new plumbing systems and retrofit of existing systems.	
Impact of current plumbing codes and standards	Workshop - 28
Prescriptive codes and standards establish minimum design and installation requirements rather than best practice. Research is needed to study the impact of current practices and assess the impact of codes and standards on premise plumbing performance. Given the influence of enforcement on compliance, and the existence of regional and local differences in codes and their enforcement, this assessment needs to cover a range of jurisdictions. Furthermore, building codes do not cover O&M or other management practices, both of which can vary based on available experience and resources. Therefore, research is needed to assess best practices with the goal of providing improved O&M tools.	
Best practice guidelines for installation	Workshop - 29; FRN - Q
Research is needed to study installation variability to better understand the impacts on water use and water quality and overall system performance, and to provide a technical basis for effective installation practices. Contractors can exercise "cost cutting" or "value engineering" during construction to reduce costs, and these deviations from design can result in systems that do not perform as originally intended. Examples of these deviations include: elimination of valves at key locations; elimination of temperature gauges at critical control points; and substitution of equipment that reduces capacity or changes the system design. Research studies of actual system installations relative to original and as-built designs could support development of best practice guidelines that are critical to proper design and operation.	
Recirculation lines and temperature maintenance	Workshop - 39
While recirculating systems exist in a range of configurations, little is known about their impacts on water quality. Investigations of current practice for recirculation lines and temperature maintenance are needed to evaluate their impacts on water quality, energy use, erosion, corrosion and scaling. This work would build off of the projects under #F3 Data.	
Water management protocols for existing buildings	Workshop - 8, 32; FRN- Q
Buildings commonly change in use and occupancy over time, and there is a need to understand the impacts of such changes on the performance of existing systems as well as the impact of retrofitting existing buildings. There is a related need to develop effective and validated management protocols to address flow reductions in existing buildings (i.e., lower flows, lower velocities and longer residence times). The results of this research could be reflected in water management and safety plans and incorporated into building management software.	
Water management strategies to control Legionella and other pathogens	Workshop - 36; FRN - C, D, F; NAS; WRF 4383
There are numerous approaches to onsite water treatment for *Legionella* and other pathogens (UV, reverse osmosis, and chemical), but the effectiveness of these strategies is not well understood. Further study is needed to inform building owners and operators of the performance of these options based on carefully designed laboratory and field studies. Best practices for water management are available, but they are not typically codified and not always implemented. This effort to assess and develop management strategies can leverage results from #F3 Data. It is also important to consider international research and practice on water treatment, including reduced reliance on utility and on-site disinfection with chlorine.	
Best practices for maintenance of emergency fixtures	Workshop - 37
Management practices (e.g., flushing) for emergency fixtures (e.g., eye wash stations, emergency showers) are set by manufacturers and standards, but many of these requirements are based on assumptions of unknown validity. Research is needed to examine these assumptions in order to support sound practices for maintaining such fixtures.	

Best practices for scheduled shutdowns and resiliency to unplanned disturbances	FRN - C
Best practices for planning scheduled shutdowns are needed, as well as for anticipating and responding to unplanned disturbances. Examples of such occurrences are water main breaks and nearby construction that can release contaminants into the water.	
Metering for low-flow systems	FRN - O, X
Best practices and guidelines for metering in low-flow water systems are currently lacking. Research is needed on meter sizing, accuracy and cost in the context of the use of low-flow fixtures and new flushometer valve designs.	
Eliminating domestic galvanized iron pipe	FRN - U; WRF 4379
The corrosion of old galvanized iron pipe is a source of deposition products that can accumulate biofilm, as well as release lead and other hazardous materials. Therefore, it is important to identify ordinances, codes, or financial policies that could support the elimination of existing domestic galvanized iron pipe.	

Potential products for Area #A2 Best Practice for Installation and Operations

- Analysis of the impacts of current design practice and code enforcement on plumbing system performance
- Analysis of the impacts of plumbing system installation on performance, including the impacts of value engineering during construction and renovation
- Assessment of current O&M practice with the goal of providing improved O&M tools
- Investigation of current practice on recirculation lines and temperature maintenance systems and their impacts on water quality and other aspects of system performance
- Analysis of impacts of changes in building use on plumbing system performance, leading to water management protocols for existing buildings
- Technical data and guidance on meter sizing for low-flow systems
- Technical data on flushometer valve design for low-flow systems
- Literature review of international research and practice on water management
- Technical assessment of the effectiveness of onsite water treatment and other management programs, leading to strategies to increase the implementation of best practices including maintenance to control *Legionella* and other OPPPs
- New software tools to address water management and water safety plans that could be integrated into building management software
- Best practices for maintenance of emergency fixtures
- Best practices for planning scheduled shutdowns and ensuring resiliency
- Policies and regulations to support the elimination of domestic galvanized iron pipe

Area #A3: Training and Guidance	
As the plumbing community seeks to leverage existing and new knowledge on water use and water quality, it will be critical to transmit this information to individual designers, building owners and operators in forms that are easy to understand and practical to apply. These mechanisms include training programs, guidance documents, and certification. Results of the research described earlier will be key to developing information needed to build a water-efficiency workforce and to increase the adoption of best practices.	
Guidance for homeowners, facility managers and other practitioners	Workshop - 16; FRN - G, P, Q; NAS
As research results are generated by the other projects contained in this report, the findings need to be translated into practical guidance for building owners, operators, and occupants. At one end of the spectrum, this guidance needs to cover more technically complex matters including operational targets for residence time, maintenance and remediation approaches (e.g., flushing, onsite treatment). Guidance is also needed for homeowners and occupants of rental units, including small commercial buildings. This guidance should include economic justifications of alternative operational and maintenance strategies.	
Training for designers on water efficiency	Workshop - 7, 11, 16, 22; FRN - B, D, S
New construction provides one-time opportunities to implement water efficiency strategies at a lower cost compared to post-construction retrofits. Based on results of the research outlined earlier, it will be critical to develop training for plumbing system designers that integrates with overall building design and architectural layout. This training should cover design parameters for residence time, access to system components for inspection and maintenance, and economic tools for analyzing alternative design approaches. This information would be useful for both practicing design professionals and students learning how to design plumbing systems.	
Training and certification for design, operation and maintenance.	FRN - Q
Training and certification programs are needed to support the design of plumbing systems that specifically address the control of microorganism growth, scalding, and overall system performance. Many engineers are not trained to design plumbing systems to control scalding and microbial growth. Furthermore, poor maintenance and operation of plumbing systems can lead to performance failures in these same areas. Training and certification programs can improve the quality of designs and promote the availability of engineers and maintenance and operation staff with the necessary skills to keep these systems performing as intended.	
Training for building water system assessments	FRN - Q
Training is needed on how to perform assessments of building water systems, as well as water-based fire suppression systems, for their overall performance with specific attention to water quality issues including the risks of OPPP growth. This training could include other systems such evaporative cooling, pools and hot tubs, and fountains.	
Maintenance and monitoring guidance for control of Legionella and other OPPPs	FRN - C; WRF 4383
There is a need for improved training and guidance on best practices for system maintenance and monitoring for the control of *Legionella* and other OPPPs. This guidance should include water treatment technologies at point-of-use, point-of-entry, tap, and the whole building, and needs to clearly distinguish between best practices and compliance with regulations.	

Potential products for Area #A3 Training and Guidance

- Guidance on premise plumbing operation and maintenance for building owners and operators, including homeowners
- Training on water efficient plumbing system design
- Training and certification programs that address design, operation, and maintenance of plumbing systems
- Training for conducting building water system assessments
- Training and guidance on best practices for system maintenance and monitoring to control *Legionella* and other OPPPs

NEXT STEPS

While this report identifies many important research needs for premise plumbing, significant efforts are needed to implement these research activities. A number of steps are proposed to convert these research needs into actionable research programs. First, an implementation plan is needed to convert these needs into a detailed roadmap for defining future research programs and projects. This roadmap would include timelines for specific programs and projects, commitments by stakeholder organizations to take the lead on various elements, and specific deliverables expected from each effort. Developing this implementation plan and roadmap will require establishment of the priority of the research needs as well as consideration of the proper sequencing of research projects to achieve the ultimate goal of efficient and safe premise plumbing systems. As an example, foundational research is needed to develop metrics and data collection protocols prior to launching efforts to evaluate system performance and collect field data. The implementation plan also needs to identify the organizations that can sponsor and carry out the research. Finally, the plan must also identify methods to disseminate the results of the research to key stakeholders who will make use of the information gained, such as standards developing organizations, professional societies that develop guidance and training programs, educational institutions that train designers and installers, and private sector firms that develop plumbing technology and design software. As noted earlier, the stakeholders who would be involved in developing the implementation plan and the research roadmap include manufacturers/trade associations, researchers, national and local government agencies, non-profit water efficiency advocates, water utilities, standards development organizations, model code bodies, code officials, educational institutions, engineering consultants, builders and developers, and others. This broad range of expertise and perspective needs to be engaged to fully cover the landscape of the research needs identified in this report and their implementation.

NIST intends to use the results of this research needs assessment to plan potential research activities in the area of premise plumbing, but NIST alone cannot meet the needs of the plumbing community in promoting efficient and safe water systems. Where appropriate to NIST's measurement science mission, NIST may identify areas in which it can start to address some of these research needs. Other organizations, such as EPA and WRF, may also use this assessment to identify potential areas for their research programs.

To engage those stakeholders who are in a position to sponsor, conduct, and utilize the research identified in this report, outreach is needed to: 1) communicate this research needs assessment, 2) to develop an implementation plan, and 3) to initiate an effort to develop a detailed roadmap that defines future research programs. NIST intends to hold webinars in 2020 to share the information contained in this report, organize a stakeholder workshop to discuss the research needs, and engage key organizations in their implementation.

CONCLUSIONS

Premise plumbing systems have evolved significantly since Roy Hunter developed systems sizing curves for the early plumbing codes. In the 1970s NBS researchers documented the challenges of prescriptive plumbing codes that at that time were insufficient to fully represent plumbing system performance. Fundamental aspects of plumbing networks have continued to evolve; new materials, changes in water usage, and changing demands for potable water necessitate a re-examination of the key gaps in standards, codes, guidelines, and design and maintenance techniques to ensure that water is delivered to building occupants in a safe manner. Recent efforts by the National Institute of Standards and Technology that led to this report summarizing research needs have included a face-to-face workshop, a Federal Register Request for Information, and discussions with industry experts and other stakeholders.

The research needs are categorized into 1) Foundational Measurement Science and 2) Applied Research. The Foundational Measurement Science needs include items such as metrics, test methods, and data that are critical to understand and characterize the physical, chemical, and biological performance of plumbing systems. Applied Research builds on the findings of the Foundational Measurement Science topics to develop guidance and design approaches to improve the efficiency of water delivery systems while improving water quality.

These research needs can be used by funding agencies and researchers to guide work aimed at improving the state of premise plumbing. Work is still needed to prioritize these needs, but the key needs that have been identified in this report serve as a starting point for focused research efforts on premise plumbing.

Acknowledgments: NIST thanks the many contributors to this report. In particular, NIST acknowledges the Steering Committee members for the August 2018 workshop: Veronica Blette and Stephanie Tanner of the U.S. Environmental Protection Agency, and Beate Wright, Maureen Hodgins, and Grace Jang of the Water Research Foundation. NIST also thanks the facilitators of that workshop, Rob Greenwood and Sarah Shadid of Ross Strategic, and Robert Pickering and Kathleen Onorevole of Eastern Research Group. Silvia Kabatova of WFT Engineering is also acknowledged for providing helpful insights into the design process. Johan Schein, Stephanie Tanner and Kevin Teichman of EPA, Pete DiMarco and Dan Cole of IAPMO, Ryan Colker and James Cika of ICC, and Maureen Hodgins and Grace Jang of WRF are acknowledged for their thoughtful reviews of this report. Finally, we thank all of those who devoted their time to provide input to this effort, either during the workshop or in responding to the Federal Register Notice.

REFERENCES

Abd-Elaal, A.E.M. and Gad, A.A.M. (2018) Improvement of plumbing systems performance using looped water pipe networks within buildings, *Journal of Water Supply Research and Technology - Aqua*, **67 (3)**, 623-633.

ASHRAE (2017) ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2017, Standard for the Design of High-Performance Green Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (2018) ANSI/ASHARE Standard 188-2018: Legionellosis: Risk Management for Building Water Systems, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASME (1955) American Standard National Plumbing Code, New York, American Society of Mechanical Engineers.

ASME (2015) Plumbing Waste Fittings, American Society of Mechanical Engineers.

ASME (2018) Plumbing Supply Fittings, American Society of Mechanical Engineers.

ASSE (2020) Professional Qualifications Standard for Legionella Water Safety and Management Personnel, ASSE International.

Balke, E.C., Healy, W.M. and Ullah, T. (2016) An assessment of efficient water heating options for an all-electric single family residence in a mixed-humid climate, *Energy and Buildings*, **133**, 371-380.

Blokker, E.M. and Pieterse-Quirijns, E. (2013) Modeling temperature in the drinking water distribution system, *Journal American Water Works Association*, **105 (3)**.

Brazeau, R.H. and Edwards, M.A. (2013) Role of Hot Water System Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution, and Sediment, *Environmental Engineering Science*, **30 (10)**, 617-627.

Buchberger, S., Omaghomi, T., Wolfe, T., Hewitt, J. and Cole, D. (2017) Peak Water Demand Study. Probability Estimates for Efficient Fixtures in Single and Multi-family Residential Buildings, Rosemont, Illinois, American Society of Plumbing Engineers. https://www.iapmo.org/media/3857/peak-water-demand-study-executive-summary.pdf

CBSC (2016) 2016 California Green Building Standards Code, CALGreen, California Code of Regulations, Title 24, Part 11, Sacramento CA, California Building Standards Commission.

CDC (2020) Health Effects of Lead Exposure, Vol. 2020, Centers for Disease Control and Prevention. https://www.cdc.gov/nceh/lead/prevention/health-effects.htm

Clark, R.M. (2015a) USEPA's distribution system water quality modeling program: A historical perspective, *World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems*, Austin Texas, 871-880.

Clark, R.M. (2015b) The USEPA's distribution system water quality modelling program: a historical perspective, *Water and Environment Journal*, **29 (3)**, 320-330.

Cochran, R.C. (1966) Measures for Progress, Washington DC, National Bureau of Standards.

DeOreo, W.B., Mayer, P.W., Dziegielewski, B. and Kiefer, J. (2016) Residential End Uses of Water, Version 2, Water Research Foundation.

DOE (2013) 2009 Residential Energy Consumption Survey (RECS), Energy Information Administration, U.S. Department of Energy. http://www.eia.gov/consumption/residential/data/2009/

DOE (2014) The Water-Energy Nexus: Challenges and Opportunities. https://www.energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf

DOE (2016) 2012 Commercial Building Energy Consumption Survey (CBECS), Energy Information Administration, U.S. Department of Energy. http://www.eia.gov/consumption/commercial/

EPA (2019) Basic Information about Lead in Drinking Water, U.S. Environmental Protection Agency. https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water#health

Falkinham, J.O., Pruden, A. and Edward, M. (2015) Opportunistic premise plumbing pathogens: increasingly important pathogens in drinking water, *Pathogens*, **4 (2)**, 373-386.

Fedak, R., Hannon, D., Taylor, Z. and Volckens, A. (2019) Developing Water Use Metrics for the Commercial and Institutional Sectors, Water Research Foundation.

Galowin, L.S. (2008) "Hunter" fixture units development, *34th CIB W062 International Symposium on Water Supply and Drainage for Buildings*, Hong Kong, 58-78.

Galowin, L.S. and Debelius, J.R. (1979) Water Supply and Drainage in Buildings, Proceedings of an International Symposium September 28-30, 1976 Washington DC, National Bureau of Standards.

Galowin, L.S., Downing, W.J., Nielsen, L.S., Orloski, M.J. and Wyly, R.S. (1979) Performance Concepts for Water Supply and Drainage Systems in Buildings, *Water Supply and Drainage in Buildings, Proceedings of an International Symposium September 28-30, 1976* Washington DC, National Bureau of Standards, 53-70.

GBI (2019) ANSI/GBI 01-2019 Green Building Assessment Protocol for Commercial Buildings, Green Building Initiative.

Grayman, W.M. (2018) History of Water Quality Modeling in Distribution System, *1st International WDSA/CCWI 2018 Joint Conference*, Kingston, Ontario, Canada.

Hanslin, R., Webster, C.D.J. and Nielsen, V. (1979) Reaearch Laboratories with CIB Interest, *Water Supply and Drainage in Buildings, Proceedings of an International Symposium September 28-30, 1976* Washington DC, National Bureau of Standards, 109-128.

Harkness, A. (1995) Building Codes: A Historical Perspective, *Building Official and Code Administrator Magazine*, **26**.

Huang, X., Pieper, K.J., Cooper, H.K., Diaz-Amaya, S., Zemlyanov, D.Y. and Whelton, A.J. (2019) Corrosion of upstream metal plumbing components impact downstream PEX pipe surface deposits and degradation, *Chemosphere*, **236**, 124329.

Hunter, R.B. (1940) Methods of estimating loads in plumbing systems, Washington DC, National Bureau of Standards.

IAPMO (2017) Water Efficiency and Sanitation Standard for the Built Environment, International Association of Plumbing and Mechanical Officials.

IAPMO (2018) Uniform Plumbing Code, International Association of Plumbing and Mechanical Officials.

ICC (2015) International Plumbing Code, International Code Council.

ICC (2016) National Green Building Standard, National Association of Home Builders of the United States.

ICC (2018a) International Building Code, International Code Council.

ICC (2018b) International Green Construction Code, International Code Council.

ICC (2018c) International Residential Code, International Code Council.

ICC (2020) ANSI/RESNET/ICC 850-2020 Standard Calculation and Labeling of the Water Use Performance of One- and Two-Family Dwellings Using the Water Rating Index, International Code Council.

Lee, J. and Whelton, A.J. (2018) Development of premise plumbing hydraulics-water quality models, *6th Biennial Emerging Water Technology Symposium*, Ontario Cslifornia.

LSLR (2020) Resources for Concerned Consumers, Vol. 2020, Lead Service Line Replacement Collaborative. https://www.lslr-collaborative.org/resources-for-concerned-consumers.html

Lytle, D.A. and Liggest, J. (2016) Impact of water quality on chlorine demand of corroding copper, *Water Research*, **92**, 11-21.

Maupin, M.A., Kenney, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L. and Linsey, K.S. (2014) Estimated use of water in the United States in 2010.

Mayer, P., Davis, S.E., Buchberger, S. and Douglas, C. (2020) Assessing Water Demand Patterns to Improve Sizing of Water Meters and Service Lines, Water Research Foundation.

Mayer, P.W., DeOreo, W.B., Opitz, E.M., Kiefer, J.C., Davis, W.Y., Dziegielewski, B. and Nelson, J.O. (1998) Residential End Uses of Water, AWWA Research Foundation and American Water Works Association.

Miller, R.W. (2019) The sixth-largest city in India is running out of water as reservoirs run dry, *USA Today*. https://www.usatoday.com/story/news/world/2019/06/20/chennai-india-water-crisis-reservoirs-run-dry-millions-need-water/1508323001/

Moerman, A., Blokker, M., Vreeburg, J. and Van der Hoek, J. (2014) Drinking water temperature modelling in domestic systems, *Procedia Engineering*, **89 (3)**, 143-150.

Monteiro, L., Figueiredo, D., Dias, S., Freitas, R., Covas, D., Menaia, J. and Coelho, S.T. (2014) Modeling of chlorine decay in drinking water supply systems using EPANET MSX, *12th International Conference on Computing and Control for the Water Industry, Ccwi2013*, **70**, 1192-1200.

National Academies of Sciences, E., and Medicine, (2019) Management of *Legionella* in Water Systems, Washington, DC, The National Academies Press.

National Research Council (2006) Drinking Water Distribution Systems: Assessing and Reducing Risks, Washington, DC, The National Academies Press.

NIBS (2016) Moving Forward: Findings and Recommendations from the Consultative Council, Washington, DC, National Institute of Building Sciences, 24.

NSF (2017) Onsite residential and commercial graywater treatment systems for subsurface discharge, NSF International.

NSF (2018a) Drinking Water System Components – Health Effects, NSF International.

NSF (2018b) Plastic Piping System Components and Related Materials, NSF International.

NSF (2018c) Residential Wastewater Treatment Systems, NSF International.

NSF (2019) Onsite Residential and Commercial Water Reuse Treatment Systems, NSF International.

Omaghomi, T. and Buchberger, S.G. (2018) Residential Water and Energy Savings in Right-Sized Premise Plumbing, *1st International WSDA/CCWI 2018 Joint Conference*, Kingston, Ontario.

Orloski, M.J. and Wyly, R.S. (1978) Performance Criteria and Plumbing System Design, Washington DC, National Bureau of Standards.

Perrier, F. (1979) Standardization Structure in Europe, *Water Supply and Drainage in Buildings, Proceedings of an International Symposium September 28-30, 1976* Washington DC, National Bureau of Standards, 89-99.

Pickering, R., Onorevole, K., Greenwood, R. and Shadid, S. (2018) Measurement Science Roadmap Workshop for Water Use Efficiency and Water Quality in Premise Plumbing Systems: August 1-2, 2018, Gaithersburg, Maryland, National Institute of Standards and Technology.

Prest, E.I., Hammes, F., van Loosdrecht, M.C.M. and Vrouwenvelder, J.S. (2016) Biological Stability of Drinking Water: Controlling Factors, Methods, and Challenges, *Frontiers in Microbiology*, **7**, 45.

Raley, C.R. (1973) 1972 International Acitivites: Center for Building Technology, Washington DC, National Bureau of Standards.

Rhoads, W.J., Pruden, A. and Edwards, M.A. (2016) Survey of green building water systems reveals elevated water age and water quality concerns, *Environ. Sci.: Water Res. Technol.*, **2**, 164-173.

Salehi, M., Abouali, M., Wang, M., Zhou, Z., Nejadhashemi, A.P., Mitchell, J., Caskey, S. and Whelton, A.J. (2018) Case study: Fixture water use and drinking water quality in a new residential green building, *Chemosphere*, **195**, 80-89.

Schück, S. (2018) Water Age in Residential Premise Plumbing. Masters, University of Arizona.

Tranchard, S. (2017) ISO Celebrates 70 Years, *ISO News*. https://www.iso.org/news/2017/02/Ref2163.html

U.S. Congress (2005) Energy Policy Act of 2005, Vol. Pub.L. 109-58.

Ullah, T. and Healy, W.M. (2016) The performance of an auxiliary heat pump water heater installed in a dual-tank system in a net-Zero energy residence, *2016 ASHRAE Winter Conference*, Orlando.

Volckens, A., Kershmab, K., Hannon, D., Taylor, Z., Fedak, R. and Sands, R. (2019) Water Use Analysis Guide for Commercial and Institutional Efficiency, Water Research Foundation.

Welch, C. (2018) How Cape Town is Coping with Its Worst Drought on Record, National Geographic. https://www.nationalgeographic.com/news/2018/02/cape-town-running-out-of-water-drought-taps-shutoff-other-cities/

Whelton, A.J. and Nguyen, T. (2013) Contaminant migration from polymeric pipes used in buried potable water distribution systems: a review, *Critical Reviews in Environmental Science and Technology* **43 (7)**, 679-751.

Whipple, G.C., Carson, H.Y., Hanley, T.F., Groeninger, W.C., Hansen, A.E., Gries, J.M., Cartwright, F.P. and Hunter, R.B. (1924) Recommended Minimum Requirements for Plumbing in Dwellings and Similar Buildings, Washington DC, National Bureau of Standards.

Whipple, G.C., Carson, H.Y., Hansen, A.E., Groeninger, W.C., Murphy, W.C., Gries, J.M., Thompson, G.N. and Hunter, R.B. (1928) Recommended minimum requirements for plumbing:

report of subcommittee on plumbing of the building code committee, Washington DC, National Bureau of Standards.

WHO (2006) Health Aspects of Plumbing, World Health Organization & World Plumbing Counci.

Woo, H., Burkhardt, J. and Rossman, L. (2018) "Modeling of Dispersion Effect for Intermittent Flow in Premise Plumbing Systems". In: Proceedings of WDSA/CCWI Joint Conference Proceedings, Vol. 1.

WRF (2019a) Green Building Design: Water Quality Considerations, Project #4383, Water Research Foundation. https://www.waterrf.org/research/projects/green-building-design-water-quality-considerations

WRF (2019b) Research Plan for Management of Emerging Pathogens Associated with Distribution Systems, Water Research Foundation. https://www.waterrf.org/research/projects/research-plan-management-emerging-pathogens-associated-distribution-systems

WRF (2019c) State of the Science and Research Needs for Opportunistic Pathogens in Premise Plumbing, Water Research Foundation. https://www.waterrf.org/research/projects/state-science-and-research-needs-opportunistic-pathogens-premise-plumbing

Wright, R.N. (2003) Building and Fire Research at NBS/NIST 1975-2000, Gaithersburg, Maryland, National Institute of Standards and Technology.

Zlatanovic, J., Moerman, A., van der Hoek, J.P., Vreeburg, J. and Blokker, M. (2017) Development and validation of a drinking water temperature model in domestic drinking water supply systems, *Urban Water Journal*, **14 (3)**, 1031-1037.

Appendix A - Prioritized Research Topics from NIST/EPA/WRF Workshop

This table contains a summary of the research topics from the workshop, copied directly from Table 1 of the workshop summary report (Pickering, et al., 2018).

	Research Topic	Rationale
1	Water quality: How do materials impact water quality (biological and chemical) over the typical lifetime of the plumbing system? (In other words, does material selection and quality impact water quality of the premise plumbing?) Do the age, condition, and type (e.g., materials, fixtures) impact the growth and persistence of OPPPs (inactivation)? Biological and chemical impacts are considered holistically with the recognition that they can be researched independently.	This is a fundamental, all-inclusive research topic.
2	Need data to better understand occupant behavior and water usage patterns for different residential and commercial building types (sequence research based on primary-use types and building types with vulnerable populations [e.g., hospitals, healthcare, daycare, and senior living]).	This is a foundational piece for establishing data, without which mistakes will be made. The success of other research items is highly dependent on this item. Current data are not consistent enough to allow comparability across buildings. Addressing this need provides a basis for understanding water turnover and efficiency factors at reduced construction cost. The research scope should not be limited to building structures and can include campuses (any point after main meter). Information can be used to reduce supply, sewer, and branch pipe sizing. Collect data at all spatial and temporal scales. Current data are lacking to inform new water demand models and improve codes. Other research needs and model development are dependent on progress in this area. **Possible subtopic:** How can new construction be used as part of data gathering (installing devices to help monitor water use/demands)?
3	Hunter's Curve needs updating, or alternatives to Hunter's Curve need development (IPC/UPC needs to reflect current and future trends in terms of low flows). Alternative sizing models (Water Demand Calculator) need to be validated and potentially improved to establish minimum and maximum pipe sizing (based on data).	Once data are collected and a new methodology is established, this item will support code revisions that will impact new building design. Codes are the primary basis for designs used by engineers and contractors. By evaluating the water demand calculator, it will provide a shortcut to other research items. The methodology used to establish Hunter's Curves considered flow rates from 80-100 years ago and is also labeled for residential only. **Possible subtopic:** How do we design systems that can operate effectively at both minimum and peak flows?

	Research Topic	Rationale
4	How do factors (physical factors such as pressure and system age and operational factors such as water age/stagnation, flow rate, water velocity, and water temperature) impact biofilm and scale and its impact on water quality within different materials (considering factors such as growth rates, type of biofilm, general biofilm characteristics, and ecology)?	Biofilms and scale are important because they are major drivers for quality problems. Biofilms and water quality are not interchangeable, and this research area brings in factors that evaluate how biofilms impact water quality. Biofilms are always in contact with water and on the premise, so they have a potentially large impact on water. Biofilms harbor pathogens and protect them from disinfectants, so it is critical to understand biofilms. New and innovative products and conservation drastically change the way systems perform, and we need to understand impacts. Because this research item is difficult to study, it hasn't yet been done, but it's important for the future. An important consideration is the type of material of the incoming pipe and its impact on water quality and pressure.
5	System performance: What is the impact of public/well/alternate source water quality (e.g., biological, chemical, disinfectant or lack thereof, physical) on the performance of the entire premise plumbing system materials and subsequent water quality over the typical lifetime of the system? (Acknowledging difference between water quality entering the building and changes that occur in the building itself, including in-building treatment).	The reverse of Priority Area 1. All-inclusive.
6	Develop a greater understanding of how water demand patterns impact water quality within premise plumbing systems.	Usage information is critical to assess real-world impact. Laboratory outcomes must be compared with real-world outcomes to fully understand risk. This topic is fundamental. Design is unlikely to dictate behavior to people (e.g., when you use the restroom), so it is important to understand behavior and design accordingly. Design is currently based on outdated behavior patterns. There is a need to understand use patterns, not just water quality, and its impact on code. Hypothesis: Use is much smaller than thought and intermittency is higher (at least for residential, may differ in commercial). There is a need to understand if this is true and its impact. **Possible subtopic:** What is the water quality at the service line versus at each outlet within the premise plumbing, and how is this impacted by usage patterns?

	Research Topic	Rationale
7	How do water age, flow rate/velocity, pressure (variations), plumbing materials, source water, in-house treatment (POU, POE), maintenance/operations, water temperature, and plumbing layout (manifold, trunk and branch, series) impact the dissipation rate of chlorine or other disinfectants?	Residual disinfectant is a primary controller of water quality.
8	Effective approaches to retrofit or manage existing buildings that are overdesigned for current and future flows.	At present, significant stock of installed buildings exists that is variable in condition, age, plumbing design, and technology. This research topic would have a larger impact than focusing on new construction. We do not know what is effective and what is not, but people are conducting retrofits in the pursuit of water efficiency or because they have a problem. One workgroup member stated that lower flows, lower velocity, and longer residence time are creating problems right now, though we don't have effective and validated management protocols in place. This is likely to become even more timely as more low-flow fixtures are installed in existing buildings.
9	Establish a common methodology or design element that allows for collection of end use data (e.g., water quality, temperature, flow rate, time-duration, frequency of data gathering). Create standardized metrics (e.g., gallons per minute [gpm], water velocity, water turnover rate).	This is a foundational research item. To collect large, usable data sets, you have to have a consistent methodology that can be applied throughout different studies. There exists a need for common language, definitions, methodology, and practice. For data standardization/classification, the workgroup suggests creation of a committee to set data standards. Establishing minimum requirements for a standard water customer classification scheme and processes will ensure uniformity in class definitions. Possible subtopic: Consider actual pipe diameter and how pipe diameter is impacted by corrosion and scaling.
10	What are the design and operation influences/risks (including super chlorination) associated with water-efficient premise plumbing with regard to water quality and materials? Side effects could include, but are not limited to, increased noise, cavitation, temperature, water hammer, pressure surges (into disinfection, water quality changes), increased erosion, pressure drop, protective function of biofilms, and scale.	This research item prevents unintended consequences and settles the conflict of turning a water heater up or down (e.g., conflict that currently exists between water and energy). It explicitly considers risk and considers materials' impacts on water, water's impacts on materials, and operational impacts on both.

	Research Topic	Rationale
11	Guidance for Designers: Establish guidance on design parameters for residence time and best management design practices to reduce overall stagnation time and residence time. Conduct an economic analysis of alternative guidance approaches and how that guidance would be validated.	This appears to be the end goal—to provide safe water. Guidance is important to provide, and it is much needed in the real world. There is a balancing act between scalding and water quality. Information can be used by practicing professionals and incoming students learning how to design plumbing systems. There are green buildings in which water sits in the system for weeks at a time. How can we impact the design to prevent this?
12	Impacts of alternative water use (e.g., net zero water, rainwater harvesting, greywater recycling) and water reuse (onsite and supplied) as it affects plumbing design and water use patterns (both drinking water and wastewater design and operation).	Alternative water uses are being codified, and there is a need to quickly understand the overall impact on design and use. Locales are already moving forward (e.g., California) and as use of alternative water continues, stagnation increases and there is an increased risk in sanitation systems. There is a need to understand impacts before rather than after we've already implemented alternative water systems.
13	Improve and validate (e.g., full-scale building tracer studies) computer models of hydraulic behavior and water quality of both hot and cold piping.	Models need to be predictive and validated with current practice. This research topic addresses lack of trust in current models (currently incomplete). Full consensus isn't possible, so there is a need for accuracy in models where we do not have complete data. Working with models will help identify where needs exist for additional information. Models are already in use, so it is important to identify which problems exist, if not to also fix those problems. How can advancements in hydraulic and water quality modeling influence building designs and code? Do we need to develop reference buildings for water (similar to those that exist for energy codes)? There is also a need to establish validation protocols to evaluate models. Possible subtopic: Mixing at junctions, mixing within pipes, temperature profiles, intermittent demands, water storage, residence time (simple guide on key characteristics and expected water age).
14	Measurement science: What are standard measurement techniques (currently no test or rating directory) to determine performance parameters for fittings and pipes (e.g., flow rate vs. pressure drop)?	There is a need for a shared language and inclusion of important definitions and parameters to prevent confusion. This is a prerequisite and a fundamental building block for design.

	Research Topic	Rationale
15	Evaluation of premise plumbing design and flushing strategies and their impacts on water quality: In light of flushing practices (drinking water quality and sanitary system flows), what is the tradeoff with conservation objectives?	This is not covered by other topics. These do not currently exist in the draw patterns and should be included where appropriate. There is a need for more science behind current recommendations. More flushing is better, but may be unnecessary. Policymakers are changing fixture flow, and it may have negative consequences, so there is a need to understand the implications to the real world. It is also important to consider conservation and outreach to the public in implementing this research item.
16	Guidance for homeowners, building facility managers, and practitioners: Establish guidance on operational targets for maximum residence time and indicators to recognize when residence time recommendations are exceeded, including suggested remediation (e.g., periodic flushing, onsite treatment). Conduct an economic analysis of alternative guidance.	Guidance for people interacting with their houses may help them understand plumbing isn't something you can ignore. This topic is so misunderstood/not thought of that people think we are keeping it a secret. This needs to be front-loaded. Would be important to include risk perception and communication. Economic analysis is important but should be balanced with conservation. At present there exists a conflicting message between conservation and need to flush.
17	Define metrics for long-term conditions: Water quality, resilience/durability, timescale (e.g., long- and short-term).	Need for a shared language and inclusion of important definitions and numeric aspects to prevent confusion. This is a fundamental building block for design. May be combined with Item #1. Given the built inventory conversation, there is a need to understand when that inventory needs to be replaced. This research item is tactical, foundational, and necessary to consider before other research areas.
18	Compile (i.e., obtain, screen, and archive) a national database of accurate, high-resolution water demand data from a wide variety of building types and end uses (e.g., residential, commercial, institutional, medical). Include context of where the data was collected (e.g., building type, location, age, occupancy).	In order to understand/compare performance, there is a need to have a national, accessible, and consistently compiled database. This is foundational for beginning to understand usage patterns and furthering other research items. Usage factors should be kept current over time (e.g., California data collaborative).
19	Influence of newer and more complex technology on design and/or management issues (e.g., mixing valves, hot water heaters, recirculation systems).	Design should be for effectiveness rather than complexity. When flows are low, dynamics are changing, but the full impact of that change is unknown. Manufacturers are trying to respond without research.
20	Data and test procedure on pressure drop and performance on modern plumbing fittings (e.g., pressure-compensating fittings, various joining techniques) at different temperatures.	If this isn't done correctly, as we move towards right-sizing systems, there is potential for error and errors embedded in data will manifest more clearly. There is a need to provide correct engineering, and this is indicative of the need to question underlying numbers for design. There is a need to review numbers in light of current materials and methods, and this research topic would feed into Hunter's Curve.

	Research Topic	Rationale
21	Wastewater/sanitary side: How do changes to premise plumbing design, incorporation of onsite reuse, reducing flow rate, etc., impact the wastewater system design (and the sanitary sewer system)?	There are existing problems in plumbing systems due to water flow reductions in the sanitary system (e.g., fixtures and appliances) and compliance with codes. Studies need to consider whether reducing the building's drainage system pipe size would result in better flow under lower flows and minimize corrosion. At present, drainage systems are turning into septic systems due to the longer residence times for waste. Changes in concentration of wastewater have impacts on materials. The Plumbing Efficiency Research Coalition (PERC) studies on drainline carry already exist to assess some commercial buildings with longer drainlines. Possible subtopics: What is the minimum flow rate required in a drainage system to move solids and ensure flow? How do we design systems that can operate effectively at both minimum and peak flows? Development of a definition for "low flow" (federal vs. states such as California).
22	Develop understanding of the interplay between building design/architecture and plumbing system design/performance.	New construction and one-time opportunities to address issues at low cost are an underrated aspect of building water quality and may have practical solutions. This research item looks towards the future—how we design new construction. Is there a good way to influence people who are coming up in design and architecture—educating the next wave of the water efficiency workforce to give a common goal?
23	Investigate hydrodynamic flow regimes and transport, which are prevalent in premise plumbing.	Hydrodynamics is not completely understood. This would act in support of thermodynamic modelling. Consider material impacts as well. Water quality is complicated to model. To create greater holistic understanding, there is a need to understand hydrodynamics. Since building water demands may be low, we may observe laminar instead of turbulent flow. Laminar flow is distinct from dispersive flow. Transport includes biota, etc.
24	What are the impacts of new technologies, materials, and water quality (upstream, in the premise side) on wastewater systems (including septic and public collection systems)?	New and innovative products have been developed, but we need a full understanding of their impacts. Already experiencing issues in the field. Possible subtopic: What is the impact of acidic condensate or effluents from high efficiency water heaters, etc.?
25	How does water velocity impact biofilm and scale growth and detachment?	It is important to understand biofilm and scale related to the movement of water and related water quality impacts.

	Research Topic	Rationale
26	Research on temperature profiles (both spatial and temporal) to guide temperature settings for water heaters (outflow curves, within water heaters, and in the hot water distribution system).	We potentially could provide actionable knowledge for guidance, if we were able to establish a better understanding. High temperature water is a critical line of defense if and when loss of residual disinfection occurs. A lot of goals are temperature-dependent. This research topic helps verify thermodynamic modelling of the plumbing systems. There are energy efficiency objectives driving temperatures one way; there is a need to better understand the balance between energy efficiency and water quality objectives. This research topic could impact how water heaters are designed.
27	Impacts of and requirements for cold and hot water recirculation systems (including hot water to cold water returns) and temperature maintenance on water quality.	Water temperature is strongly related to water quality (pathogen regrowth). These types of systems are more frequent and being mandated in some areas, and we need to better understand the impact on water quality and how to manage the systems to control for water quality impacts.
28	How to objectively measure/quantify impact of codes and standards on premise plumbing water quality?	Codes and standards are the basic, minimum requirement, and it is critical to understand how current approaches may have side effects or unintended consequences. Possible subtopics: To what degree are codes being enforced? How does enforcement differ regionally? What version of the code should be compared?
29	Installation: What are the impacts of improper installation on water quality and system performance? How can we impact installation based on that information?	Installation impacts system performance. An understanding of installation variability will provide a basis to better promote effective practices to ultimately have positive impacts on system performance and water quality.
30	Measurement science objective: Capturing a way to describe the chemical and biological stability of influent water using select parameters.	This item provides a starting point to mitigate risk. Influent water quality/conditions affect all aspects of the premise plumbing system and the appropriateness of system management approaches. Understanding influent water stability can better inform what effective system management practices will be. It is unclear, however, which metrics would be used for prediction, in part given the variability of influent water conditions. There are some metrics for stability that can act as a starting point.
31	Impact of combined hydronic/potable systems (stagnancy, time spent circulating in heating system, biofilm and scale growth in water pathway) on water quality.	Combined systems are theoretically breeding grounds for pathogens, and there has been a lack of attention on symptoms up to now. Possible subtopic: Efficacy and best management practices of exercising methodologies and intermittent cycling (e.g., hydronic air handlers).
32	How do the changes in occupancy and use impact the efficacy of the existing premise plumbing?	Buildings are always going to have changes in use and occupancy, and we need to understand impacts on efficacy.

	Research Topic	Rationale
33	Water heater type and operation and related influence on water quality.	All occupied buildings have a water heater, and temperature is an overarching consideration. Better understanding can help with existing and new buildings' fuel type, capacity, and mixing characteristics. Thorough assessment of water heater performance with regards to pathogens would fill a huge gap. Different water heaters perform differently with regard to temperature. Efficient heaters perform differently with regard to pathogen growth. There is current, large societal investment (tax credits) to promote efficient heaters without information on their impact on pathogens. Possible subtopic: Net-zero carbon and water heaters as storage.
34	Influence of dead-ends/dead-legs (either from incomplete renovations or roughed in for future plumbing) on water flow, age, and quality.	Dead-ends exist in every building, and if there is a detriment it should be understood. Dead-ends are inevitable, yet unresearched. How are dead-ends established (for future expansion vs. by incomplete renovations)?
35	Water quality and scaling impacts on pressure drop, material selection, design, etc.	Scaling plays a complex role in the plumbing system (reduces heat exchanger performance, degrades pipes, integral to water quality) and yet requires additional research, as it is not well understood. For example, scaling may increase pathogens, but protect against lead (i.e., scaling helps prevent erosion, corrosion).
36	Investigating international approaches to design and treatment that reduce reliance on disinfection (with regards to the utility and premise).	This item is low-hanging fruit. We are stuck in a chlorine-residual bubble and need to consider other alternatives. The research is already complete.
37	Establish emergency fixtures (i.e., eye wash stations, emergency showers) best management practices (e.g., flushing) as required by manufacturers/standards.	We have long runs of hot and cold water piping to provide tepid water to emergency fixtures. Requirements are based on assumptions not on fact, and we should develop requirements based on facts. (Note: Emergency fixtures do not include fire sprinklers.) Possible subtopic: Manufacturers currently set requirements for flushing—are they sufficient? Excessive? Not going far enough?
38	Investigate opportunities to foster competitive or "beneficial" biofilms and scale, including designing biofilm communities to improve water quality.	Biofilm is inevitable, and understanding how to encourage good growth is important. It's a future item, but it's never too early to start on the future.

	Research Topic	Rationale
39	Investigate current construction best practices for recirculation lines and temperature maintenance systems (e.g., mitigate biofilm and scale buildup) with the intention of improving them in the future, with water quality, energy, and erosion/corrosion/scale as investigative endpoints.	Many of these systems exist, and not much is known about how they impact water quality. Controls and strategies will be different on simple and complex systems.
40	Establish a protocol to identify plumbing design of existing buildings.	We have limited understanding of existing building premise plumbing system characteristics. This leaves a gap relative to formulating renovation and management practice recommendations for proper system operation.
41	Resolving ongoing research regarding pipe diameter as it influences biofilm and scale growth, which may depend on variations in surface area contact inside pipe.	Practice is trending towards smaller diameter pipes. New information is indicating that it may be problematic from a microbiological standpoint, and there is a need to understand this quickly. An important aspect is the influence of pipe diameter on flow regime and the related influence on biofilm growth and detachment.
42	Impact of multipurpose residential piping or limited area sprinkler systems on water quality.	Systems can or may have substantial amounts of stagnant water at one temperature, and that has the potential to act as a breeding ground for pathogens. Requirements for fire sprinklers are adopted in state code for residential structures.
43	Establish standard classifications and sub-classifications for multifamily and commercial, institutional, and industrial (CII) building types (consider existing census and DOE classifications) to support collection of consistent information conducive to capture in a centralized database.	[Rationale not discussed during workshop due to time constraints.]
44	Develop methods to apply existing data sets on water end-use accounting to similar building types (e.g., multifamily and CII subcategories). For example, can information from Residential End Uses of Water be applied to the multifamily sector?	[Rationale not discussed during workshop due to time constraints.]
45	Information to improve plumbing and sewer modeling to be used with BIM (building information modeling) platforms.	[Rationale not discussed during workshop due to time constraints.]
46	Run-out length and diameter related to end-use flow rates.	[Rationale not discussed during workshop due to time constraints.]

	Research Topic	Rationale
47	Material compatibility: How does the use of mixed materials in a system (material compatibility) impact water quality and the integrity of the system?	[Rationale not discussed during workshop due to time constraints.]
48	What is the impact of electrical grounding to pipes?	[Rationale not discussed during workshop due to time constraints.]

Appendix B –Input Received in Response to Federal Register Notice

This table contains a summary of the input submitted to NIST. The actual submittals were much longer and detailed but were summarized for the purposes of this table.

Response	Topic
A	Understanding water use in buildings Health risk assessment for efficiency measures Simulation tools for water flow in buildings Drinking water quality in airplanes
B	Quality of water quality data used for monitoring and assessment. Reaction of piping material with water treatment chemicals • Corrosion of copper piping • Brittling of PVC, CPVC, PEX • Levels of chlorine, chlorine dioxide, ozone, and copper silver ions in water • Effectiveness of treatment chemicals on reducing microbial agents, critical levels Relation between microbial growth and • Water age • Microbial biofilm • Effectiveness of water management/treatment efforts
C	Design strategies for minimizing surface area of piping and fixtures Design strategies to minimize stagnation Management practices to avoid introduction of foul water into major lines Design data and strategies for temperature management of water in piping Data to characterize disinfectant levels at POE and POU for various building types and systems Better methods for sample collection, record keeping, and testing for *legionella* Best practices for planning for scheduled shutdowns and unplanned incidents such as water main breaks Outreach/education and information to support value proposition to implement best practices versus marginal compliance with minimum regulation
D	Understanding presence and growth of OPPPs, and how plumbing system design and operation plays a role due to: • Temperature • Stagnation • Water age • Biofilm formation and its promotion of bacteria growth Can pipe materials and surfaces be designed to inhibit biofilm growth and colonization? Some pathogens are developing resistance to certain disinfectants; need to understand the mechanism

E	Understanding of how water is used in buildings • Flow rate • Volume • Timing • Variability Reliable data on water use with modern fixtures and design Understanding performance and impacts of materials used in plumbing systems over time Field measurements of water samples from across the United States
F	Design to inhibit growth of *Legionella* Maintenance of plumbing systems and monitoring for *Legionella*
G	Improve design and sizing requirements Temperature considerations to balance health, safety, and energy Disinfection techniques Designs that reduce stagnation Understanding the complex interplay between water chemistry and biological impacts Understanding tradeoffs between safety, functionality, and cost Long term studies of piping systems for various materials Guidance for maintenance
H	Understanding growth rate of suspended and fixed biomass Understanding how materials play a role in growth (roughness, etc.) Understanding mechanisms for materials to leach into water Better methods for water sampling: locations, frequency, collection procedure, preservation, transfer, analytical methods, quality assurance Increase knowledge/awareness among consumers
I	Characterizing the effectiveness of water management strategies Characterizing the effectiveness of onsite water treatment (e.g., UV, reverse osmosis, and chemical) Building Information Management systems for water quality and occupant water usage
J	Standards for certification of lead free or non-lead leaching pipes, fittings, and fixtures
K	Scientifically sound data to ground debate on hot water temperature Need benchmarks for water usage in various types of buildings Suggests that increased use of PVC, CPVC, HDPE, and other plastics in lieu of copper has changed the biofilm characteristics. Need to understand how materials and biofilms are related Data from metering at POU level is needed to enable future reductions in consumption Continuous real-time monitoring of water throughout entire plumbing system

L	Review all recorded incidents to correlate fixtures and equipment with higher risk of pathogen growth and transmission; try to replicate findings in lab setting to verify Better understanding of temperature influence on pathogen production Understand how pathogen growth is affected (positively or negatively) in various materials Review all recorded incidents to correlate stagnation and excess water storage with risk of pathogen growth and transmission; try to replicate findings in lab setting to verify Studies to identify additional measures that could be used to protect high-risk populations from pathogenic diseases Review all recorded incidents to correlate disinfectant additives with risk of pathogen growth and transmission; try to replicate findings in lab setting to verify Assess risks for cross connections, pathogen growth and transmission, and water quality for non-potable water. Need guidance for developing policies
M	What is the extent of water contamination upstream and within a building? i.e. how much effort should be spent targeting each? For main water supply to buildings, what is the concentration of chemical, metallic, biological, etc. contaminants? How does this change with ambient water temperature, precipitation, seasonal change, pressure disruption/variation, chlorine burn, or other water chemistry changes? How much is random and how much is predictable? What are reasonable action levels for various pathogens? Are there any possible proxy methods for determination of OPPPs? Current testing and remediation methods are costly.
N	Need data to better understand where and how much water is used in buildings. Studies of monitored buildings with a high degree of granularity are needed. Can't really fix anything until we have this knowledge Need to understand pressure losses associated with today's more diverse plumbing system materials, fittings, and components Need better understanding of material sciences as they pertain to biofilms and pathogen growth in plumbing systems Understanding the implications of further water flow reductions Determine feasibility of separate water distributions for potable applications Need probabilistic model for estimating drainage loads with modern flows, in order to properly size drain lines Data to support vent sizing requirements in drainage systems
O	Need accurate estimates for peak water demand expected for particular end uses served by a variety of fixtures Better and less expensive meters are needed to enable data capture Computer model to simulate instantaneous flow, heat, and water quality of a premise plumbing system. Linkage to Building Information Modeling (BIM) platform would be beneficial Understand whether dispersive transport is important in plumbing systems Determine practical limits of innovative developments; i.e. should we target net-zero water, limitations for rainwater or greywater
P	Understanding relationship between disturbances such as nearby construction and contaminants released into water Data on monitoring point of entry and point of use for OPPPs, PFAS, microplastics, lead, and arsenic

	Characterizing the scale of treatment and delivery for all types of buildings within public water systems Estimates of energy savings achievable through high-efficiency water treatment Holistic review of environmental initiatives with their impacts
Q	Information to inform training and guides for design and maintenance. Commenter stated that most problems he investigates are initiated by a lack of understanding Information is lacking to ensure that construction team cost-cutting eliminations and/or substitutions do not usurp important features Water management and safety plans should be incorporated into building management software Understanding chemistry and microbiology within plumbing systems Understanding advantages and disadvantages of test methods to identify chemical residuals and microorganisms, and develop improved methods Understanding temperature effects on microbial growth and disinfection rates How to properly perform a building water system assessment for plumbing systems. Also stated same need for evaporative cooling systems, pools and hot tubs, fountains, irrigation systems, fire suppression systems, and industrial systems
R	Need leadership in efforts to understand and protect against *Legionella* outbreaks
S	Need data to inform codes, specifically range and mean values for: • Daily water usage • Service line length and diameter • Length and diameter of hot and cold plumbing in buildings • Incoming water pressure • Hot water temp at tap • Residence time at each branch of system In the following building types: • Single family homes • Multi-family buildings • Commercial • Hospitals • Day care facilities • Assisted living • Industrial buildings • Multi-building campuses Explore current water reuse practices in various municipalities, and examine benefits/tradeoffs and impact on water quality and overall performance Study the effects of efficiency measures for specific equipment, such as cooling towers, and the unintended health consequences and mitigation opportunities Multi-building/campus systems can be very complex. Conservation opportunities and health risk opportunities should be explored on this scale

T	Single definition of plumbing system and premise plumbing Determine effectiveness of engineering controls for control and management of biofilms in plumbing systems Optimize hot water systems to balance control of microbial hazards and scalding Data needed to improve distribution sizing with current fixtures Data needed to reduce stagnation and control temperatures Understand the link between water quality and fixture type and plumbing material Need effective methods to communicate technical information
U	Need water quality standards Need better methods and equipment for testing water quality in plumbing piping, also availability/cost are barriers. Specific contaminants fall into three main groups: bacteria, metals, and chemicals Need water quality targets and test procedures specific to type of facility (population served, types of piping, geographic area, etc.) Identification of a 'control' point within internal system to assist with testing Guidance for best practices of remediation strategies and tools Understanding how water quality factors and conditions affect the potential for piping and cooling towers to be environments for growth of biofilms as media for accumulation of undesirable pathogens What are the most significant factors that should be controlled and what techniques are successful and under what specific conditions for each (role of nutrients, nitrates, phosphates, pH, alkalinity, turbidity, dissolved solids, temperature, time) What can be done at the building entry point to reduce potential for growth/regrowth Identifying the key factors that allow *Legionella* and other microbes to enter a premise piping system Understanding how various disinfectants perform in different environments, specific performance characteristics for Cl; ClO_2 and chloramine. Do Cl^-, Br^-, or sulfates affect copper and/or silver ions? Should hot and cold water systems be managed differently due to different issues? Explore possibilities and tradeoffs How can we effectively control corrosion to mitigate formation and resuspension of deposited matter. How can we eliminate remaining domestic galvanized iron pipe Design and configuration characteristics of piping systems for energy conservation and reducing water stagnation Need established guiding principles to address the cause of water quality degradation and waste
V	Comparison of traditional dead-end water distribution system with closed-loop continuous flow circuits without two step decontamination and disinfection. Same as first item but with reversible flow Same as first item but with two-step decontamination and disinfection Same as above, but with reversible flow Compare traditional copper and iron water systems to flexible plastics Study temperature variability throughout entire system and the impact on biofilm growth
W	Explore relationship and mechanisms for low-flow and electronic devices leading to biofilm and growth of pathogens

X	Understand chemical precipitation in drain lines due to low-flow fixtures Minimum flow rates through plumbing fixtures needed to carry solids through drains Meter sizing based on low-flow fixture counts Pipe sizing based on low-flow fixture counts Influence of pipe roughness leading to capacity limitations Submetering Understanding and practices to mitigate water hammer Research alternate cross connection testing methods Water reuse – impacts on water chemistry from blending multiple water sources Metering water reuse systems
Y	Better methods for testing distribution mains for *Legionella* and other pathogens, need to identify specific strains at this level to help understand how it grows and is transported Better methods and devices for continuously testing chlorine levels from public water supply entering buildings

Appendix C - Design and Analysis Tools

DESIGN TOOLS		
	Description of capabilities	**Highlighted Features**
CADRE Flow **(latest: v.3 2019)**	• Flow rates, pressures, losses, and velocity • Hydraulic grade lines, energy lines • Power available, required, and lost • Forces on joints and fittings • Joint and fitting losses • Pump requirements • Turbine requirements, unit discharge • Cavitation detection and evaluation • Vary viscosity, temperature, and vapor pressure within the system • Unrestricted variations of the Reynolds number within the system (laminar, turbulent, transition) • Unlimited complex 3D networks and piping layouts • Automatic environmental conditions and fluid setups for common fluids in any system of units • Easily handle low speed flow systems (biofilters)	• Energy consumption
CAEPIPE Piping Stress Analysis **(v9.01 2019)**	• Integrate new + existing plumbing design, merging of models • Incorporates different US, Canadian, and European piping codes for evaluating compliance. (e.g. ASME B31, ASME Section III, European EN) Also, equipment standards (NEMA, API, etc.) • Databases/libraries • Pipe materials, insulation materials, pipe sizes, valve and connection libraries	• System stresses
Pipe Flow Expert **(v7.6 2016)**	• Fluid flow in open or closed loop pipe networks with multiple supply & discharge tanks, multiple pumps in series or in parallel, and multiple pipe sizes & fittings. • Allows for isometric 3D piping layouts • Includes database for fluid, pipe materials, and fittings data	
Trane™ Pipe Designer **(v4.1 2012)**	• Determine required pipe sizes, pump sizing, valve pressure drops, and the effects of elevation change.	• Bill of materials and cost

	• Three pipe materials: steel, copper, and PVC. • Generate a complete bill of material, estimate system material and/or installed costs. • Calculations using viscosity and specific gravity of any fluid. • Can analyze hybrid systems (new/existing piping and reverse-return layouts • Open and closed systems	
Water Demand Calculator **(v1.4 2019)**	• Predict the peak water demand for single and multi-family dwellings having water-conserving plumbing fixtures	• Water demand
ANALYSIS TOOLS		
	Description of capabilities	**Highlighted Features**
Applied Flow Technology (AFT) Fathom **(v.10)**	• Experiment with operating conditions and scenarios • Easily change system input data, including valve positions, pump operation, control set points, pressures, temperatures and more • Import piping layouts and dimensional data from GIS shapefiles, CAESAR II Neutral files and Piping Component Files (*.pcf) from AutoCAD Plant 3D, SmartPlant®, CADWorx® and others. • EPANET import / export Excel integration • Model a wide range of system components for both design and operational cases • Vary your system line-up: open / close pipes and valves, turn pumps on or off, set control valves to fail position • Specify alerts that automatically highlight output values that are out of range for flow, pressure, velocity, pump efficiency and more • Select pumps from online manufacturer catalogs • Compile catalogs of your frequently used piping components and select them from a drop-down list • Address the viscosity and frictional changes associated with pumping non-settling slurries and a variety of other non-Newtonian fluids • Calculate the cost of system pipes and components • Clearly import Excel data into multiple scenarios and export with the Excel Export Manager.	• EPANET import/export integration • Plumbing design/operation

COMSOL Multiphysics - FLUID FLOW & HEAT TRANSFER MODULES **(v5.4)**	• Simulations of fully-developed fluid flow, heat and mass transfer, hydraulic transients, and acoustics in pipe and channel networks • Models heat and mass transfer and material transport within pipe networks (e.g. diffusion, convection, dispersion, and chemical reactions)	• Transients
EPANET **(v2)**	• Extended-period simulation of hydraulics and water quality in water distribution systems • Used to design and size new water infrastructure, retrofit existing aging infrastructure, optimize operations of tanks and pumps, reduce energy usage, investigate water quality problems, and prepare for emergencies • Models transport of reactive and non-reactive materials • EPANET-MSX (Multi-Species eXtension): Can model complex reactions of chemical and biological species • EPANET-RTX (Real–Time eXtension): Uses real-time operation inputs to calibrated, verified, and continually tested data • Programmer's Toolkit: Allows users to customize EPANET for their own needs. Functions written in C/C++, Visual Basic, or any other language that can call functions within a Windows DLL	• Extended-period simulation • Customizable back-end
FloMASTER **(v9)**	• 1D computational fluid dynamics (CFD) model • Understanding how design alterations, component choice and configurations, and operating conditions affect pipe flow dynamics • Thermal and hydraulic models • Steady state and transient modeling • Empirical data libraries • Experiments feature allows for sensitivity and parametric analyses • Monte Carlo simulations: based on probability distribution generated from mean and standard dev for selected input parameters.	• 1D-CFD • EPANET co-sim capability
HVAC Solution Pro **(v9.4.1 2018)**	• 2D, object-oriented HVAC system modeling	

	• Can model hydronic and steam systems	
HydrauliCAD	• Water system design and hydraulic analysis • Water modeling inside of AutoCAD using the industry standard EPANET simulation modeling engine	• Design as well as pipe network analysis • EPANET import/export integration
InfoWater	• Simulates movement, concentration, and fate of water quality constituents (such as chlorine and fluoride residuals) • Calculates water age, and computes over time the percentage of water originating from any specified source location • Simulates conservative and reactive species as well as the more advanced multiple substance accumulation/decay.	
NextGen Hydraulic Pipeline Simulation Suite	• Complex residential network modeling • Nodes, Meters (unlimited number of meters per node), water wells as nodes/meters (ARPS, PLE), pipes, detailed pump stations (3 unit types), regulators, valves, check valves, storage tanks, process plants, warmers/chillers, flow meters, wells as legs, leaks • Oddly-shaped water towers (nonlinear pressure/volume relationships) • Water well modeling • Temperature tracking, source tracking, revenue tracking • Built in equations for viscosity and other parameters • Supports systems sizes of 1,000,000+ nodes for steady state and sequential.	
WaterGEMS **(subprogram of** WaterCAD**)**	• Analyze pipe and valve criticality • Assess fire flow capacity • Build and manage hydraulic models • Design water distribution systems • Develop flushing plans • Identify water loss • Manage energy use • Prioritize pipe renewal • Simulate networks in real time	• Energy consumption
WATSYS	• Simulate existing distribution system to identify and correct deficiencies and to predict a system's performance during	

	such emergencies as pump failures, main breaks, equipment malfunctions or fire flows. • Used to design expanded system to meet future demands • It may be used to carry out simulations for peak usage periods and low demand cycles. • Performs water quality analysis including chlorine decay, fluoride distribution, source tracing and water age	