NIST Technical Note
NIST TN 2256

November 2022 NIST Premise Plumbing Research Workshop: Summary and Findings

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Building Energy and Environment Division
Engineering Laboratory

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NIST Author ORCID iDs

Andrew Persily: 0000-0002-9542-3318
Marylia Duarte Batista: 0000-0002-5200-7963
William Healy: 0000-0001-7711-7301
Mark Kedzierski: 0000-0001-5051-1819
Lingnan Lin: 0000-0002-0813-7613
Tania Ullah: 0000-0001-6588-8977
David Yashar: 0000-0002-8532-8501
Stephen M. Zimmerman: 0000-0002-5254-278X

Abstract

Premise plumbing systems need to meet a range of performance goals including occupant health and comfort, energy and water efficiency, and reduced environmental impacts. Pressures to improve water efficiency and building water quality, combined with the use of new plumbing technologies and designs, have led to the recognition that significant knowledge gaps exist in plumbing system design, installation, operation, and maintenance. The research needed to address these gaps was summarized in a 2020 NIST report *Measurement Science Research Needs for Premise Plumbing Systems*. NIST also initiated an effort in 2020 to study several key research topics identified in that report including: the pressure versus flow relationships of plumbing fittings, the factors contributing to pathogen growth in residential hot water systems, the development of standard plumbing systems for comparing different design and operational approaches, and the improvement of existing premise plumbing system simulation software. To obtain feedback from industry and others in the premise plumbing community, NIST held a one-day workshop in November 2022 to discuss these research efforts, strengthen ongoing dialogues among the plumbing community, and develop a shared understanding of the research needs.

Keywords

Measurement science; premise plumbing; research needs; water; workshop.

Table of Contents

List of Tables

1. Introduction

Premise plumbing systems constitute an essential component of the built environment by providing access to clean, potable water and a safe, reliable means of removing wastewater from homes, businesses, and other institutions. Plumbing systems evolved throughout the 20th century in response to concerns about cost, water availability, environmental impacts, and safety. The National Bureau of Standards (NBS), the predecessor to the National Institute of Standards and Technology (NIST), performed research that supported and informed these advancements throughout most of the 20th century.

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 policies led to notable achievements including the reduction of lead in plumbing products and the introduction of high-efficiency fixtures. 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 (Persily et al. 2020). For example, a typical single-family, detached home today uses 22 % less water for indoor purposes than it did two decades ago (DeOreo, Mayer et al. 2016). Consequently, the flow rates within the piping networks and the corresponding residence times are significantly different than those assumed under current design methods. This situation has in turn led to questions regarding the assumptions surrounding the effectiveness of water treatment practices and concerns regarding the potential for decreased water quality.

In response to these realities and in recognition of the need for research needed to provide new data and technical understanding of plumbing system performance, NIST, the U.S. Environmental Protection Agency (EPA), and the Water Research Foundation (WRF) jointly hosted a workshop in August 2018. The objective of this workshop was to identify and discuss research needs to support the design and operation of new premise plumbing systems and the management of existing systems given the realities of lower water consumption and the needs for increased water and energy efficiency and for improved water quality. This event was attended by 46 representatives from industry, academia, government, utilities, and standards and codes organizations. The workshop proceedings were published in Pickering, Onorevole et al. (2018).

Subsequent to the 2018 workshop, NIST solicited additional input through a request for information (RFI) that was published in the Federal Register in October 2018. This RFI generated 26 responses from a broad array of interested parties, including over 140 pages of text on the most important issues to design and operate safe, healthy, reliable, and efficient plumbing systems and the research needed to address these issues. Additional discussions with other organizations provided another important source of information. For example, the International Association of Plumbing and Mechanical Officials (IAPMO) and the International Code Council (ICC) are the two major model code development organizations within the premise plumbing community, and discussions with both provided important information to NIST. Follow up discussions with the WRF, EPA, numerous advocacy groups, and academic researchers were also a key resource.

NIST used the information obtained through these mechanisms 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 (Persily et al. 2020). The 59 research needs published in that 2020 report were 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 understanding and characterizing the physical, chemical, and biological performance of plumbing systems. Applied Research builds on the findings of the Foundational Measurement Science to develop guidance and design approaches to improve the efficiency of the water delivery systems while also improving water quality.

Shortly after that report was published, NIST initiated a research program to pursue a subset of the research needs in the 2020 report. A workshop was held on November 15, 2022 to present and discuss the NIST research efforts with industry and others in the premise plumbing community. In addition, this workshop was intended to continue ongoing dialogues within the plumbing community and develop a shared understanding of the research needs. This report contains the material presented during that workshop and summarizes the discussion that took place. Section 2 of this report reviews the workshop agenda and the topics discussed. Section 3 summarizes input obtained from the participants prior to the workshop in combination with the discussion that took place during the event. Section 4 contains a summary of the workshop findings and describes next steps to continue the dialog and maintain the interest expressed during the workshop. This report also contains two appendices: A – a list of attendees and their affiliations, and B – the presentation materials from the workshop speakers.

2. Workshop Agenda

The workshop agenda is shown in Table 1. Most of the morning was devoted to presentations on the NIST premise plumbing research efforts, including tours of two laboratories designed and instrumented over the previous 2 years. After the tours, Steven Buchberger of the University of Cincinnati described his work funded by NIST under a cooperative agreement. All other research projects were conducted by NIST staff and research associates based at the NIST Gaithersburg, MD campus. Following the NIST project presentations, there were discussions of related activities being pursued by other federal agencies or with EPA funding. During the afternoon, the attendees discussed industry trends and activities and research priorities.

Table 1. Workshop Agenda.

NIST Premise Plumbing Research Workshop
15 November 2022
National Institute of Standards and Technology
Building 226, Room B205
Gaithersburg Maryland

Time	**Agenda Item**
7:30	Registration starts at NIST visitors center. Optional tour of Net-Zero Energy Residential Test Facility.
Transition to Building 226, Room B205 (NIST staff escort required from lobby of Building 226)	
8:30 to 9:00 a.m.	**Welcomes and introductions**
9:00 to 9:40 a.m.	**NIST premise plumbing research (Part 1)** Water heaters and pathogen growth Water Heater Laboratory – Marylia Duarte Batista Testing at NIST Net Zero Energy House – Tania Ullah Pressure v. flow of plumbing fittings – Lingnan Lin
BREAK	
9:55 to 10:45 a.m.	**Lab tours:** Pressure v. flow of plumbing fittings Water heaters and pathogen growth (Water Heater Laboratory)
10:45 to 11:25 a.m.	**NIST premise plumbing research (Part 2)** Non-residential Water Use – Steven Buchberger Model Development – Mark Kedzierski Standard Plumbing System Designs – Stephen Zimmerman
11:25 a.m. to Noon	**Premise plumbing research activities under other federal agencies** Jonah Schein, US EPA, Office of Water Jeff Szabo, US EPA, Office of Research and Development Michael Blanford, HUD Patrick Gurian on EPA-Funded research program – Drexel University Andrew Whelton on EPA-Funded research program – Purdue University
LUNCH	
1:00 to 2:00 p.m.	**Discussion of plumbing industry trends and activities** Andrew Whelton on disaster impacts on plumbing – Purdue University Christoph Lohr on industry trends - IAPMO
2:00 to 3:00 p.m.	**Discussion of research priorities**
3:00 to 4:00 p.m.	**Wrap-up and Follow-up**

The six NIST presentations are summarized as follows, with the slides from each in Appendix B of this report.

Water Heaters and Pathogen Growth: Water Heater Laboratory

A new laboratory facility was built at NIST to study the response of opportunistic premise plumbing pathogens (OPPP) to water use patterns and temperature settings in electric storage water heaters. OPPP are waterborne microorganisms in potable water that can persist and grow in building plumbing, increasing the likelihood of infections in immunocompromised and elderly individuals. The experimental design consists of three steps: tank cleaning, in which tanks are disinfected and heavily flushed; an acclimation phase, in which the heaters operate at low temperature and low usage to allow microbial growth; and an experimental phase, in which each tank temperature is raised to a different setting [49 °C (120 °F) and 60 °C (140 °F)] and a planned water use pattern is implemented. Water samples are collected for analysis of bench-scale physical/chemical water quality parameters, molecular analysis of OPPP through ddPCR, and culturing of heterotrophic microorganisms. Future expansion of the test setup will include testing of different types of water heaters and components, such as pipes, fixtures, and thermostatic mixing valves.

Water Heaters and Pathogen Growth: Testing at the NZERTF

This project is investigating the effects of water heater setpoint temperatures and water use patterns on the occurrence and concentrations of OPPP in an automated test home on the NIST campus. This residence is equipped with a heat pump water heater and a PEX-manifold plumbing system to provide hot and cold water for a 4-person building occupancy. Chemical and physical water quality parameters and concentrations of OPPP such as *L. pneumophila*, *P. aeruginosa*, *M. avium*, and *N. fowleri* were measured at the building water supply line, the cold and hot water plumbing systems, and the fixtures. Preliminary results show that *L. pneumophila*, the bacterium that causes Legionnaires' disease, had the highest number of detects (25 % of n = 60 samples), though the frequency of detection of any pathogen was small. Results of this study will aid researchers and policy makers in identifying strategies to reduce OPPP growth in buildings and their associated health impacts.

Pressure v. Flow of Plumbing Fittings

Pressure loss characterization of plumbing fittings has been identified as a fundamental measurement science gap. However, there is no standardized method of test to develop pressure-flow curves in fittings, and existing data are not sufficiently accurate to support the increasingly demanding design processes to improve water and energy efficiency. The lack of a scientific, standardized method to quantify pressure losses through plumbing components also confounds efforts to address oversized water supply systems, which can support the growth of OPPP and lead to delayed hot water delivery. NIST reviewed available data and published a summary of that review (Lin et al. 2022). NIST also designed and constructed a new laboratory facility to establish a standardized and precise means of establishing pressure-flow relationships of plumbing fittings. This laboratory includes state-of-the-art instrumentation to accurately measure water flow and pressure drop for a range of fittings using approaches identified in collaboration with NIST's Fluid Metrology Group in the Physical Measurement Laboratory. Data will be acquired in this laboratory for a range of fittings and components, and a draft method of test will be submitted to an appropriate standards development organization for further development and consideration as an industry consensus standard.

Model Development

Models of premise plumbing temperatures and mycobacteria dynamics have been improved in two separate efforts. First, EPANET, which was developed for outdoor water distribution systems, could be improved by including heat transfer and corresponding local temperature prediction. To support these improvements, NIST paid a royalty-fee to the TRNSYS developer to allow inclusion of its Type604 pipe heat transfer model into EPANET. Inclusion of the TRNSYS model in EPANET is being pursued by the EPA's Water Infrastructure Division, which oversees the distribution of EPANET. The second effort has produced a promising model for nontuberculous mycobacteria (NTM) dynamics in plumbing systems, which was developed by modifying an existing NIST model derived to predict the thickness of the contaminant excess layer on piping surfaces. The original model was developed using in-situ measurements obtained from a fluorescence-based measurement technique and accounts for turbulent convection and diffusion of contaminant from the surface. The original model was modified by converting the contaminant thickness to a rate of reduction in the contaminant excess layer as the pipe is flushed. The modified model captures the rate of NTM colonization in a pipe during a prescribed stagnation period as a function of diameter, velocity, disinfectant residual, and other parameters.

Standard Plumbing System Designs

Standardized reference buildings have been developed for evaluating energy and indoor air quality performance of residential and commercial buildings by the U.S. Department of Energy and NIST, which have been very useful for conducting a wide range of research studies and for developing revisions to existing standards (Persily et al., 2006; Ng et al. 2019). Under this project, NIST developed premise plumbing system designs for a subset of these reference buildings under a contract with an architectural and engineering firm. These designs include two single-family detached homes, a four-story multi-family residential building, a medium sized office building, a stand-alone retail building, a primary school, and a full-service restaurant. These plumbing system designs and the associated documentation will be made available to the public on NIST's website to support consistent analyses of plumbing system performance and the impacts of different technologies, design approaches, and operating strategies.

Non-Residential Water Use

This effort involved three sub-tasks performed by the University of Cincinnati (UC) under a cooperative agreement funded by NIST:

Task 1 - Develop a wireless sensor network to monitor use of individual fixtures in buildings. Extending the Water Demand Calculator (Buchberger et al. 2017) to non-residential buildings requires realistic estimates of the probability of use of individual water fixtures (i.e., "p-values"). To acquire these p-values, an innovative wireless sensor network with distributed modules, routers and a gateway was developed. The non-intrusive sensor network was designed to record all instances when water was flowing at a particular fixture. Field testing was conducted at two buildings on the UC campus, demonstrating the technical feasibility of this novel data collection scheme for estimating fixture p-values.

Task 2 - Identify non-residential building stock, determine sample size, and estimate fixture p-values. Based on surveys from several federal agencies, five types of non-residential buildings were recommended for peak flow monitoring: education, healthcare, lodging, office, and food sales/service (DOE 2018, EPA 2017). The number of building fixtures to be sampled to achieve statistically significant results was identified using sampling theory. A procedure was then proposed for archiving field observations from the wireless sensor network. Methods were explored to analyze these data and extract representative estimates of the fixture p-values. Finally, Monte Carlo techniques were used to simulate fixture use and confirm that estimated fixture p-values converged to a steady-state result.

Task 3 – Corroborate predictions of the Water Demand Calculator (WDC). The Water Demand Calculator predicts the 99th percentile of the peak flow during the busy hour of water use in residential buildings fitted with water-conserving fixtures. Indoor water use at 20 newly constructed residential buildings totaling 1267 apartments in California (12 sites), New York (6 sites) and Washington (2 sites) was monitored for an extended period. Results showed that predictions of peak water use from conventional methods (e.g., Uniform Plumbing Code-Hunter's Curve) were, on average, 12 times higher than instantaneous peaks measured in the field. In contrast, WDC predictions of the peak water use were only three times higher, on average, than the peak water demands observed at the residential sites. This field verification exercise showed that, compared to the conventional Uniform Plumbing Code approach, the WDC provided more accurate estimates of the actual peak water demand, while still affording a comfortable margin of safety.

The presentations under the agenda item "Premise plumbing research activities under other federal agencies" are provided in Appendix B of this report.

3. Pre-Workshop Input and Workshop Discussion

This section of the report summarizes the input submitted to NIST before the workshop as well as the discussion that took place during the workshop. This material is organized around the 59 research needs published in the 2020 NIST report with additional needs that were discussed noted as such. After the presentations of NIST research efforts and research efforts under other federal agencies, there was a broader discussion of industry trends and activities, which are captured in Section 3.2 Other Trends, Activities and Needs.

3.1. Input and Discussion on Research Needs

Prior to the workshop, NIST contacted the attendees with questions for them to consider in preparation for the discussion, and some individuals sent their thoughts to NIST in advance. The specific questions were:

- Which of the research needs in the 2020 NIST research needs report do you think are most pressing?
- Are there new research topics that need to be addressed since that report was published?
- What do you see as the major trends in the premise plumbing field that need to be addressed through research or guidance development?

This section merges the pre-workshop input with the discussion that took place during the meeting itself. That material is organized using the research needs and their numbering in the 2020 report, starting with Foundational Measurement Science (identified by F) and followed by Applied Research (identified with an A). Research needs that were identified as "most pressing" are in **bold font**, along with any comments provided, noted with an *, **, + or ++ symbol. However, the fact that specific research needs were not identified as pressing by the attendees does not necessarily mean they are not important. After each table of research needs, additional input, discussion, and potential research topics are noted in ***bold italics***. These comments and suggestions for additional research topics were generated by the workshop participants and do not reflect NIST positions or the results of NIST research efforts.

Areas #F1 and #F2: No response on either.

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

*Need to update and validate methods to predict demand

*Also need to understand plumbing system performance under various conditions of use (pressure changes, lower flows, etc.).

*Field surveys to acquire representative, high-accuracy, high-resolution data in a variety of commercial, residential, and institutional buildings as well as multi-building campuses, including multi-family, mixed-use, hospitals, schools, daycare, and assisted living.

*Need to consider income ranges to help target research efforts and implementation actions. See the Census Bureau's American Housing Survey's (AHS) data on household income, which is crossed with other important factors, including units in structure and year built.

**Consideration of occupant behavior and water usage must address building occupancy changes in response to the pandemic, many of which will remain in place for the long term.

Impact of pressure drop on biofilms.

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 systems
Improved venting requirements based on modern system demands

*Water age as a metric, including impacts of system sizing and piping layout, e.g., dead ends.

Understanding how transitioning to plastic materials may or may not impact short- and long-term water quality.

Impacts of smaller pipe sizes on pipe longevity and noise.

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

*Pressure losses as a function of materials and fitting geometry are critical for modern materials and fittings, particularly given the need to right-size the piping

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*

*If the WDC predicts smaller supply demands and the need for smaller pipe, then something very similar should be true on the drainage side.

Improved ability to model water distribution systems, including updating Hunter's method into a computer program that can be used in building design.

A robust public-domain user-friendly computer program to simulate the detailed and stochastic operation of premise plumbing systems with output linked to BIM platforms that can be used to fine-tune the hydraulic design of new buildings. Such a program could also generate information on water residence times, maintenance (flushing) plans and identify locations in premise plumbing systems that may be susceptible to water quality problems.

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++

* Codes are on 3-year cycles, followed by additional time for local adoptions; we need to get ahead of this schedule through research and education.

** Not all designs are equal. For example, recirculation system designs may be single- or multi-zone, one heater may be used for hot water needs or there may be distributed and clustered heaters. Must consider water delivery, not just water heating.

+ Specifically, technical assessment of alternative water systems is needed to address rainwater harvesting and on-site reuse.

++Water age and pipe right sizing, as well as drainage and venting design.

Reducing plumbing system "footprint" can lead to lower water volume, which could improve water quality, and will reduce material costs.

Methods to predict peak water demands to properly design systems in new buildings.

Bringing the Water Demand Calculator into non-residential construction.

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

Microbial water quality indicators for non-legionella premise plumbing pathogens.

Mycobacteria are not as well understood as Legionella.

Impacts of disinfection strategies on biological growth and plumbing materials.

The use of building intelligence to reduce water age and repurpose water for other on-site applications, such as irrigation and laundry.

Impact of wording in the Safe Drinking Water Act of 1974 that considers a building owner who treats potable water in their building to control Legionella to be a public water system.

Scalding management for safety, public health, and energy; knowledge exists but improved guidance needed.

The typical plumbing system has two key control variables - temperature and flushing. We understand temperature well, but not the impact of flushing frequency, volume, and rates.

State Codes are being pushed by commercial entities to include water management plans, testing and certification before research is finished.

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

*Training should also include assessments of water-based fire suppression systems for overall performance with specific attention to water quality issues including risks of OPPP growth.

3.2. Other Trends, Activities and Needs

Several other topics were discussed during the workshop under the agenda item on industry trends and activities, and that discussion is captured below. These comments were made by the workshop participants and do not reflect NIST positions or the results of NIST research efforts.

<u>Sustainability (which includes water and energy efficiency, and decarbonization)</u>

- Pipe layout, which impacts energy use and water age, is driven to a large degree by the architectural layout of a building. Better training is needed for architects to understand the importance of layout for minimizing piping lengths and system footprint.
- Holistic research and design are needed to support system optimization.
- Hot water sides of systems are increasing in size (i.e., storage volume) and temperature setting, which has energy implications.
- Better information is needed on the relationships between scalding risk, energy costs, and OPPP growth.
- Decentralized water treatment and reuse has potential that needs to be better understood.
- Solar PV and sanitary venting are competing for space on residential rooftops.
- Policy initiatives to decarbonize water heating are promoting the installation of heat pump water heaters instead of other water heating technologies. These systems are very different and require different design strategies and space considerations.
- These same initiatives are also addressing reduced water storage volumes in pipes, which can adversely impact plumbing safety.

<u>Resilience and Other Infrastructure Issues</u>

- Guidance needed to decontaminate plumbing systems, including remediation strategies for buildings of different size, e.g., single-family homes, larger commercial buildings, etc.
- Research to help provide uniform and scientifically sound guidance to deal with contamination by per- and polyfluorinated substances (PFAS).
- Better understanding of the impacts of nitrification, which may be widespread but not always harmful in terms of pH reduction.
- Evaluation of methods to reduce the number of non-flood water loss insurance claims.
- Wastewater treatment infrastructure needs to be improved.
- The need for water efficiency is expected to become more pressing because of population growth, climate change and infrastructure challenges. Resilience needs to be acknowledged as key to these realities.
- Infrastructure and guidance to plan for intermittent water supply.
- What to do when plumbing systems are contaminated, i.e., what chemicals are most persistent and how to decontaminate?
- Wildfire Issues: After fires, contaminated water can get into the treatment plants, and they are not equipped to treat it. Recommendations are not always based on science. For example, benzene has been found in water systems, which raises questions of how much time is needed to flush the system or does it need to be replaced?

<u>Water Quality/Water Safety</u>

- Low flow becomes efficient flow if the whole building is designed for low flow, not just the fixtures. Many other elements of premise plumbing systems are still grossly oversized.

- Water quality requirements are needed for indoor potable and non-potable use that are safe for the occupants and do not jeopardize the performance of a plumbing system and its components.
- Improved hydraulic designs are needed for efficiency and cost effectiveness, while managing the risk from OPPP.
- Flushing/increasing flow rates often is the chosen solution to water quality issues but without necessarily fully understanding the problem.

Innovation, Design, Affordability and Other Technical Needs

- The U.S. requires more vent piping than many other countries, even with the same performance goals.
- Drainage systems are also currently oversized.
- Simplified plumbing fixtures and systems are needed to reduce pressure losses, surface area available for potential biofilm growth, and stagnant water conditions that increase water age and the likelihood of OPPP growth.
- Reducing plumbing system "footprint" can lead to lower water volume, which could improve water quality and reduce material costs.
- The design of modern devices can create areas at risk of increased microbial activity. Also, it can be difficult to take some components apart without breaking pipe. We need fixtures that can be repaired easily.
- Right-sizing supply piping saves money and reduces the volume of plumbing systems. And while the use of the WDC is growing slowly, it is expected to ramp up rapidly. We need data to extend its use to other occupancies, and we need to teach the industry that it is safe to use and how to know whether it is being done correctly.
- While there is a lot of focus on new construction, there are millions of buildings that were built before 1992; how do we cost-effectively manage water quality risks and deliver the expected service in these buildings?
- The modeling of plumbing systems for building design needs to be improved. Digitization of plumbing design, along with the entire design process, would be helpful in meeting this need.
- Continuous commissioning is needed for premise plumbing, but best practices are needed to support these processes.
- Building insurance/warranties could include mechanisms to pay for commissioning.

Specific technologies

- Vacuum water closet technology, urine separating water closets, and onsite wastewater composting technology are receiving attention in the international plumbing community as the need for net zero water and nutrient recovery increases.
- Questions exist regarding the impact of wastewater separation (from different streams within building, e.g., so called greywater) on horizontal drain line transport. It was noted that some international approaches, such as those used in Germany, the Netherlands and China, may be able to provide some useful insight.
- The airflow around heat pump water heaters and the associated performance impacts needs to be better understood to improve installation guidance.
- The technical understanding of the effectiveness and impacts of thermostatic mixing valves needs to be improved. For example, some have raised concerns about "collateral heating" of cold water lines associated with mixing valves and the potential for water quality issues.

- Point-of-use water heaters and electric water heaters with tanks may benefit from new design features driven by new and anticipated research findings. These new features may lead to the need for design standards and certification processes that are evidence-based.
- Better guidance is needed on target hardness levels for water softeners.

4. Summary and Next Steps

As is evident in the above material, the workshop discussion covered a wide range of topics related to the ultimate goals of improving energy and water efficiency and water quality in premise plumbing systems. The discussion on research needs and other issues facing the industry and others involved in premise plumbing are summarized below.

Several key trends, both new and old, that are affecting premise plumbing system design and operation were identified and discussed including energy efficiency, reduced greenhouse gas emissions, decarbonization, infrastructure, resilience and natural disasters, and population growth and movement.

The key priorities for research and other activities that were highlighted include the following:

Data on water usage patterns in buildings and microbial growth in plumbing systems.

Models of building water use, as well as biological growth, thermal performance, flow and pressure, and water age in premise plumbing systems. Also, standard reference plumbing system designs.

Water heating energy performance; water temperature management to balance energy use, safety, and pathogen growth; and existing and new technologies.

New technologies that hold promise for improved performance, but which also lead to questions on implementation and actual performance.

Science-based guidance and standards for design, installation, maintenance, and system assessment; including guidance that specifically targets homeowners.

Tables 2 and 3 are drawn from the 2020 NIST Research Needs report (Persily et al. 2020), with topics that were identified as important during the workshop highlighted in **bold**. Additional research needs discussed during the workshop are added and highlighted in ***bold italics.***

Table 2. Updated 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
Impact of pressure drop on biofilms.
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
Understanding how transitioning to plastic materials may or may not impact short- and long-term water quality.
Impacts of smaller pipe sizes on pipe longevity and noise.
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
Improved ability to model water distribution systems, including updating Hunter's method into a computer program that can be used in the design process.
A robust public-domain user-friendly computer program to simulate the detailed and stochastic operation of premise plumbing systems with output linked to BIM platforms that can be used to fine-tune the hydraulic design of new buildings. Such a program could also generate information on water residence times, maintenance (flushing) plans and identify locations in premise plumbing systems that may be susceptible to water quality problems.

Table 3. Updated 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
Methods to predict peak water demands to properly design (right-size) premise plumbing systems in new buildings.
Bringing the Water Demand Calculator into non-residential construction
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
Microbial water quality indicators for non-legionella premise plumbing pathogens.
The use of building intelligence to reduce water age and repurpose water for other on-site applications, such as irrigation and laundry.
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

Major themes that arose repeatedly during the workshop were the need to right-size plumbing systems, impacts of water source, the need to address system drainage and venting in addition to water supply, and approaches to deal with the many challenges in existing buildings as opposed to focusing exclusively on new building designs. The need for research to reflect real plumbing systems and to employ a holistic approach was another important theme during the discussion.

The workshop closed with a discussion of next steps and follow-on activities. The attendees were all committed to continuing the dialog at conferences and other venues, and to identifying and pursuing vehicles to advance the discussion and move the field forward.

5. References

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Appendix A. List of Workshop Attendees

Julius Ballanco, Self
Michael Blanford, HUD
Steven Buchberger, University of Cincinnati
Richard W. Church, CM Services
Dan Cole, IAPMO
Michael Cudahy, PPFA
Peter De Marco, IAPMO
James E. Dipping, ESD
Marcus Elmer, Copper Development Association
Mark Fasel, ICC
Patrick Gurian, Drexel University
David A. Hewitt, HUD
Timothy M. Keane, Legionella Risk Management
Gary Klein, Self
Cliff Kornegay, HUD
Jasen Kunz, CDC
John Lansing, PAE
Christoph Lohr, IAPMO
Mia Catharine Mattioli, CDC
Toritseju (Toju) Omaghomi, University of Cincinnati
Jonah Schein, US EPA
Matt Sigler, ICC
Kerry Stackpole, PMI
Jeffrey Szabo, US EPA
Kyle Thompson, PMI
Andrew Whelton, Purdue University

NIST Staff
Marylia Duarte Batista
Joannie Chin
William Healy
Mark Kedzierski
Lingnan Lin
Lisa Ng
Natascha Milesi Ferretti
Denise Nyangwechi
Andrew Persily
Tania Ullah
David Yashar
Stephen Zimmerman

Appendix B. Workshop Presentations

NIST presentations

NIST Agenda and Discussion

Design and operation of a NIST laboratory facility to study opportunistic premise plumbing pathogen (OPPP) occurrence in hot water systems; Marylia Duarte Batista

Impacts of Water Demand and Water Heater Delivery Temperatures on Opportunistic Premise

Plumbing Pathogens in a Single-Family Residence, Tania Ullah

Measuring Pressure Losses in Modern Plumbing Fittings, Lingnan Lin

Non-Residential Water Use, Steven Buchberger and Toju Omaghomi (University of Cincinnati)

Comparing Measured Peak Flow Rates to WDC Estimates, Gary Klein

Enhanced Plumbing System Simulation Tools, Mark Kedzierski

Standardized Plumbing System Models, Stephen Zimmerman

Non-NIST presentations

U.S. EPA WaterSense Update, Jonah Schein

U.S. EPA Premise Plumbing Research, Jeff Szabo

Water Quality in Buildings (Results of EPA sponsored study), Patrick Gurian

Right Sizing Tomorrow's Water Systems for Efficiency, Sustainability, & Public Health (Results

of EPA sponsored study), Andrew Whelton

Disaster Impacts on Plumbing, Andrew Whelton

21st Century Water Needs, Christoph Lohr