Water Quality, Water Savings and the Water-Energy Nexus
Three Issues, One Solution?

By

Part 1 - Marc Edwards

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America’s Water Infrastructure is Failing

Water Mains
- 240,000 leaks/year due to corrosion (EPA 2010)
- $200 billion for safe drinking water/next 10 years (Shanaghan 2012)

Building Plumbing
- ≈ 750,000 leaks/year
- $1 billion/year for consumers
  (Scardina et al. 2007)

Maryland, March 19 2013

13 leaks/foot of copper pipe in one case
Corrosion
250,000 main breaks per year and rising...
The New Challenge: Opportunistic Premise Plumbing Pathogens (OPPPPs):
Key Issues

- Why OPPPs, Why Now?
- Taking Responsibility for OPPPs
- OPPPs in green buildings
Growth of Opportunistic Pathogens

- Primary cause of waterborne disease in US

- **Legionella pneumophila**
  - 8K-18K cases/yr
  - $430M/yr
  - Cause of all 31 reported respiratory waterborne disease outbreaks 2007-10

- **Mycobacterium avium**
  - 100 cases/10^5 people >60yrs
  - $425M/yr
  - Only recently linked to drinking water

- **Pseudomonas aeruginosa**
  - 11,000 HAIs from 1992-93
  - No required reporting

- **Naegleria fowleri**
  - “Brain eating amoeba” – 2 recent high profile cases linked to drinking water

References: 1-5
Why Increasing Incidence of OPPPs?

- Improved detection and diagnosis
- Warming planet and buildings
- More time spent indoors (from 80% to 90% in 20 years)
- Changing demographics and immuno status
  - Rising levels of obesity, elderly, asthma, allergies
- Sustainable buildings and cities?
  - Water conservation/green building/water reuse
  - Tighter buildings

**OPPPs control will be the key water-related public health battlefield of the 21\textsuperscript{st} Century**
Taking Responsibility for OPPPs
Amplification of OPPPs

Water Treatment Plant or Point of Entry:
Characteristic AOC, Nutrients, Temperature, Disinfectant Type and Dose

Service line (Lead, PVC, Galvanized, Copper)

< 1 day

1-5 days

> 2 weeks

PVC main
Iron main
Cement main

Storage/Booster disinfection

Recirculating line

Softener

Low flow shower
High flow shower
Shower with filter

Leaded faucet
Unleaded faucet
Metered faucet

Tankless heater

Point-of-use filter

In-building Disinfection

Standard heater with Al or Mg Rod

Filter

< 1 day
Engineering Control Strategies

1) Limiting Nutrient Strategies (e.g., AOC)
2) Secondary Residual Type and Dose
3) Upgrade Water Mains
4) **Water Heater Set Point**
5) In-Building Disinfection
6) Thermal Shock Treatments
7) Pipe Material Selection
8) Flow Control
9) Heater Selection
10) Water Age
Water Heater Set Point

Concept: Achieving temperatures > 60 ° throughout plumbing system severely limits regrowth of all OPPPs

Limitations (Rhoads et al., 2014):

- Not an option in systems with scaling
- Higher “E” costs (scaling, more losses)
- Scalding concerns (probably over-rated)
- Higher temperatures can sometimes mean much more OPPPs at distal taps
Hot Water Plumbing Rig

William Rhoads

Research

Water heater temperature set point and water use patterns influence *Legionella pneumophila* and associated microorganisms at the tap

William J. Rhoads*, Pan Ji, Amy Pruden and Marc A. Edwards

Abstract

**Background:** Lowering water heater temperature set points and using less drinking water are common approaches to conserving water and energy; yet, there are discrepancies in past literature regarding the effects of water heater temperature and water use patterns on the occurrence of opportunistic pathogens, in particular *Legionella pneumophila*. Our objective was to conduct a controlled, repeated pilot-scale investigation to address this knowledge gap using continuously recirculating water heaters to examine live water heater set points (59–58 °C) under three water use conditions. We hypothesized that *L. pneumophila* levels at the tap depend on the collective influence of water heater temperature, flow frequency, and the resident plumbing ecology.

**Results:** We confirmed temperature setting to be a critical factor in suppressing *L. pneumophila* growth both in continuously recirculating hot water lines and at distal taps. For example, at 51 °C, planktonic *L. pneumophila* in recirculating lines was reduced by a factor of 2.87 compared to 39 °C and was prevented from re-colonizing biofilm. However, *L. pneumophila* still persisted up to 58 °C, with evidence that it was growing under the conditions of this study. Further, exposure to 51 °C water in a low-use tap appeared to optimally select for *L. pneumophila* (e.g., 125 times greater numbers than in high-use taps). We subsequently explored relationships among *L. pneumophila* and other ecologically relevant microbes, noting that elevated temperature did not have a general disinfecting effect in terms of total bacterial numbers. We documented the relationship between *L. pneumophila* and *Legionella* spp, and noted several instances of correlations with *Vermamoeba vermiformis*, and generally found that there is a dynamic relationship with this amoeba host over the range of temperatures and water use frequencies examined.

**Conclusions:** Our study provides a new window of understanding into the microbial ecology of potable hot water systems and helps to resolve past discrepancies in the literature regarding the influence of water temperature and stagnation on *L. pneumophila*, which is the cause of a growing number of outbreaks. This work is especially timely, given society's movement towards "green" buildings and the need to reconcile innovations in building design with public health.

**Keywords:** *Legionella pneumophila*, Hot water, Stagnation, Water use, Temperature
Simulating Hot Water Plumbing

Factors studied:
Temperature x time for *L. pneumophila*

Distal Taps cooled to room T in 20 minutes!
More *L. pneumophila* re-growth at warm (not hot) T
## A L. pneumophila concentration (log gene copies/mL)

<table>
<thead>
<tr>
<th></th>
<th>Control System (39° C)</th>
<th>Experimental System (39° C)</th>
<th>Water Use Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Use Frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>5 months</td>
<td>4.2</td>
<td>4.2</td>
<td>4.1</td>
</tr>
<tr>
<td>8 months</td>
<td>4.2</td>
<td>3.4</td>
<td>3.9</td>
</tr>
<tr>
<td>13 months</td>
<td>4.3</td>
<td>4.7</td>
<td>4.3</td>
</tr>
<tr>
<td>15 months</td>
<td>5.1</td>
<td>4.8</td>
<td>4.3</td>
</tr>
</tbody>
</table>

## B L. pneumophila regrowth factor (distal taps/recirculating lines)

<table>
<thead>
<tr>
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<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>5 months</td>
<td>0.8</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>8 months</td>
<td>4.2</td>
<td>0.7</td>
<td>2.1</td>
</tr>
<tr>
<td>13 months</td>
<td>1.9</td>
<td>5.6</td>
<td>1.9</td>
</tr>
<tr>
<td>15 months</td>
<td>5.5</td>
<td>3.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

## C Total L. pneumophila yield per week (log gene copies)

<table>
<thead>
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<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>5 months</td>
<td>6.9</td>
<td>7.4</td>
<td>8.1</td>
</tr>
<tr>
<td>8 months</td>
<td>6.9</td>
<td>6.6</td>
<td>7.9</td>
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<td>15 months</td>
<td>7.8</td>
<td>8.0</td>
<td>8.4</td>
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"Sweet Spot"
Engineering Control Strategies

1) Limiting Nutrient Strategies (e.g., AOC)
2) Secondary Residual Type and Dose
3) Upgrade Water Mains
4) Water Heater Set Point
5) In-Building Disinfection
6) Thermal Shock Treatments
7) Pipe Material Selection
8) Flow Control
9) Heater Selection
10) Water Age
<table>
<thead>
<tr>
<th>Target Gene</th>
<th>Orientation</th>
<th>No Chloramine</th>
<th>Chloramine</th>
<th>No Chloramine</th>
<th>Chloramine</th>
<th>No Chloramine</th>
<th>Chloramine</th>
<th>No Chloramine</th>
<th>Chloramine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>L. pneumophila</strong></td>
<td>Recirc</td>
<td>4.2</td>
<td>2.2</td>
<td>4.0</td>
<td>2.3</td>
<td>4.0</td>
<td>2.3</td>
<td>4.4</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>No Mixing</td>
<td>4.5</td>
<td>4.0</td>
<td>4.0</td>
<td>3.1</td>
<td>4.4</td>
<td>3.1</td>
<td>4.4</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Mixing</td>
<td>5.0</td>
<td>4.4</td>
<td>4.4</td>
<td>5.0</td>
<td>4.4</td>
<td>5.0</td>
<td>4.4</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Mycobacteria spp.</strong></td>
<td>Recirc</td>
<td>3.6</td>
<td>4.4</td>
<td>3.6</td>
<td>4.4</td>
<td>3.6</td>
<td>4.4</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
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<td>5.0</td>
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<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Mixing</td>
<td>5.2</td>
<td>6.0</td>
<td>6.0</td>
<td>5.7</td>
<td>6.0</td>
<td>5.7</td>
<td>6.0</td>
<td>5.7</td>
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</tbody>
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10-50X MORE Mycobacteria spp.
Engineering Control Strategies

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10) Water Age
Flow Rate (Pipe Velocity) Conceptual Model

Flow Direction
Flow Rate (Pipe Velocity) Conceptual Model
Flow Rate (Pipe Velocity) Conceptual Model

LOW FLOW
Flow Rate (Pipe Velocity) Conceptual Model
Flow Rate (Pipe Velocity) Conceptual Model
Flow Rate (Pipe Velocity) Conceptual Model
Flow Rate (Pipe Velocity) Conceptual Model
Flow Rate (Pipe Velocity) Conceptual Model

\[ \frac{dCl_2}{dt} \]

LOW FLOW

[diagram showing flow rate and related calculations]
Proving the Obvious

Clear PVC after repeated flushes with water containing humic acid

- 0.2 gpm: 82% retained
- 0.6 gpm: 60% retained
- 2.6 gpm: 8% retained
Engineering Control Strategies

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9) **Heater Selection**
10) Water Age
Role of Hot Water System Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution, and Sediment

Randi H. Brazeau\textsuperscript{1,*} and Marc A. Edwards\textsuperscript{2}

\textsuperscript{1}Department of Earth and Atmospheric Sciences, Metropolitan State University of Denver, Denver, Colorado.
\textsuperscript{2}Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Received: December 19, 2012  Accepted in revised form: July 13, 2013
<table>
<thead>
<tr>
<th>Parameter</th>
<th>STAND</th>
<th>RECIRC</th>
<th>DEMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Tank: Stratifies; bottom as much as 25°C cooler than top Pipes: Cool to ambient (25°C)</td>
<td>Tank: Homogenous Pipes: Heated to tank temperature</td>
<td>Tank: Not Applicable Pipes: Cool to ambient (25°C)</td>
</tr>
<tr>
<td>Total chloramine residual</td>
<td>24–66% higher than RECIRC in bulk water</td>
<td>Improved delivery of disinfectant to biofilm</td>
<td>Virtually no decay from distribution system levels</td>
</tr>
<tr>
<td>Hydrogen; sediment</td>
<td>H₂ lower than RECIRC</td>
<td>Circulation delivers H₂ directly to pipe biofilm</td>
<td>Extremely low H₂; no sediment accumulation</td>
</tr>
<tr>
<td>DO</td>
<td>Overall higher than RECIRC</td>
<td>Lower DO leads to increased growth of microaerophile</td>
<td>Highest levels of DO</td>
</tr>
<tr>
<td>Total copper</td>
<td>6–13 times lower than RECIRC</td>
<td>310–750 ppb</td>
<td>Similar to STAND</td>
</tr>
<tr>
<td>Flow reversal; mass transport</td>
<td>None, low transport</td>
<td>Flow reversal in pipes, high transport</td>
<td>None</td>
</tr>
<tr>
<td>to pipe wall</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Engineering Control Strategies

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Buildings with high water age are more likely to be colonized with opportunistic pathogens.

<table>
<thead>
<tr>
<th>Building</th>
<th>Water Age</th>
<th>Cause of Water Age</th>
<th>Pathogens detected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEED office</td>
<td>8 days</td>
<td>Large # of infrequently used fixtures</td>
<td>Yes</td>
</tr>
<tr>
<td>Net-zero office</td>
<td>2-6 months</td>
<td>Rainwater cistern</td>
<td>Yes</td>
</tr>
<tr>
<td>Net-zero energy house</td>
<td>2.5 days</td>
<td>Solar water heater</td>
<td>Yes</td>
</tr>
<tr>
<td>Conventional House</td>
<td>&lt;1 day</td>
<td>NA</td>
<td>No</td>
</tr>
</tbody>
</table>
Acknowledgements

- Water Research Foundation
  - Project 4379: Literature Review and Prioritization of OPPPs Research
  - Project 4383: Water Quality Problems in Green Buildings
  - Project 4251: Relationship Between Biodegradable Organic Matter and Pathogen Concentrations in Premise Plumbing
- Alfred P. Sloan Foundation Microbiology of the Built Environment Program
- National Science Foundation Grants 1033498 and 1336550
- Copper Development Association
- Tim Keane/Consumers/Managers on the OPPPs Front line
Conclusions:

– Solutions that can be implemented by utilities
  • Maintaining higher chlorine residuals
  • Upgraded infrastructure

– Solutions that can be implemented by building owners
  • Higher temperatures
  • In building disinfection
  • Flow velocity control
  • Heater type and operation
  • Water age
Thank You!
edwardsm@vt.edu

Co-authors:
- William Rhoads
- Amy Pruden

Collaborator:
- Annie Pearce

Water Research Foundation

Project 4383: Green Building Design
Water Quality Considerations

Microbiology of the
Built Environment

Edwards’ Research Group
Lack of corrosion control = Increased *Legionella*

1. More bacteria “food” in river
2. Iron corrosion = more iron entering buildings’ pipes
3. High iron corrosion removed chlorine disinfectant
Flint learns of Legionnaires' disease spike as water crisis continues

Legionella Outbreak in Flint Leads to 87 Cases, 10 Deaths; Water Crisis Connection Unclear