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Buildera Application Note AN-14001

COLD-SHOWER MYSTERY SOLVED

Multi-Channel Data Loggers Improve Forensic Analysis of Complex Domestic Hot Water Complaints

By Greg Lowitz

Figure 1. Residential hot-water thermostat set to 120°F temperature range.

Highlights

- Resolve cold-shower complaints
- Understand thermal stacking
- Measure thermostat hysteresis
- Prevent scalding
- Improve occupant satisfaction
- Reduce callbacks

Audience

- Building inspectors
- Forensic engineers
- General contractors
- Homeowners
- Plumbing & HVAC contractors
- Property & maintenance managers
- Superintendents

Problem Summary

An energy-conscious homeowner complained of insufficient hot water during morning and evening showers, particularly in warmer months. Yet, at other times of the day, and during colder winter months, hot water was plentiful—approaching scalding temperatures in excess of 120ºF. The occupant set the thermostat to the manufacturer's recommended energy-saving setting, which remained unchanged since installation. Flushing the hot-water tank and accumulated sediment failed to significantly raise hot-water temperature during first use.

Prior to forensic analysis, the homeowner suspected the water heater was due for replacement—an estimated $1,200 repair—including parts and labor. To solve this mystery, Buildera conducted a non-invasive, scientific analysis of the hot-water system and thermostat hysteresis using a battery-operated four-channel temperature logger. To assist contractors, homeowners, inspectors, and property-maintenance managers on challenging hot-water issues, this application note details the troubleshooting methodology, practical tips, and solutions.

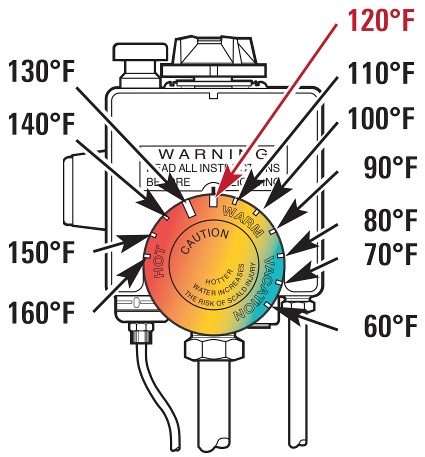
Key Facts

- Hot-water temperature was inconsistent, particularly on first use in the morning or evening
- Insufficient hot water was more common in warmer (summer) months, but typically hotter during colder (winter) months
- For successive showers (within 30-120 minutes), the second shower had sufficient hot water whereas the first shower did not
- Each shower had independent hot and cold water valves, not newer-style pressure-balancing or temperature-limiting mixing valves
- The 2500-square-foot home was built in 1994
- Walls, ceilings, floors, and hot water pipes were insulated in accordance with California Title-24 energy standards in force at the time of construction
- Hot-water points-of-use included three bathrooms, a kitchen, and laundry room with sink
- The heater was a 12-year 50-gallon GE natural-gas tank heater with dual sacrificial anodes
- Tank was located inside the first-floor utility closet with an outside combustion-air intake
- The water heater age at the time of evaluation was approximately 9 years
- Robert Shaw model R110RTSP thermostat was set to an operating temperature of 120ºF
- Approximate pipe run from hot water heater to first shower was 15 feet (5 meters)
- Water delivery system was 3/4" type L copper inlet and outlet
- System included insulated 1/2" copper recirculating line returning to the bottom of the water heater, which the homeowner had previously disabled to conserve energy

Gas Water-Heating Principles—Practical Review

Despite increased adoption of tankless water heaters in North America, gas and electric-storage water heaters dominate for most single-family, light-commercial, and multi-unit dwellings. Operational simplicity and more efficient designs deliver energy factors (EF) between .60 to .90 and above. For clarity, this application note focuses on traditional gas storage water heaters with a center flue, although many safety principles, including scald prevention, also pertain to electric and high-efficiency gas models.

Figure 2 shows a typical gas-fired water-heater thermostat sporting an analog dial with continuously variable settings, ranging from VACATION mode to HOT (some manufacturers label the top-end VERY HOT). Across this dial range, the temperature varies from a low of 60-80°F to a high of 150-160°F. Tank manufacturers, the EPA (Environmental Protection Agency), and many municipalities recommend a target setting of 120°F for energy efficiency and scald mitigation. Yet, OSHA, the American Society of Plumbing Engineers (ASPE), and Legionella experts advise at least 140°F-water to kill harmful bacteria [1-3].


Hot-Water Thermostat Temperature Settings

TEMPERATURES ARE APPROXIMATE

Figure 2. Typical gas-fired heater thermostats vary from 60°F to 160°F. Most owners manuals recommend a 120°F energy-saving setting. Adapted from GE owners manual.

To reduce accidental scalding and keep monthly bills in check, most energy-conscious homeowners set their water heater to the recommended 120°F setting. Figure 3 illustrates thermostat setting versus scald time for healthy adults. Note that infants, children, and the elderly have thinner skin or slower reaction times, hence are more susceptible to irreversible burns, even at moderately elevated temperatures. Property owners and maintenance personnel must pay particular attention to scald prevention for such occupants. For example, an adult exposed to 140°F water would experience irreversible second or third-degree burns in just five seconds. Clearly, water this hot is extremely dangerous and can cause severe injury to the most resilient adults, let alone children, disabled, or elderly persons.

Thermostat Setting vs. Scald Time

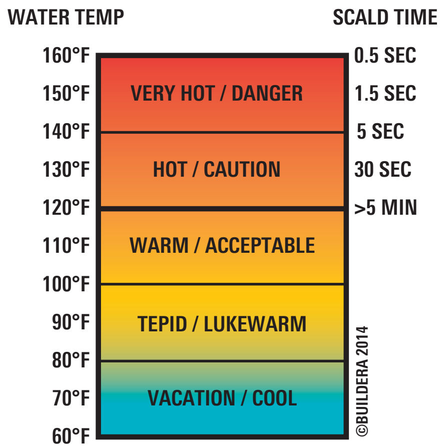


Figure 3. Thermostat setting vs temperature and scald (burn) rate for adult skin. Infants, children, and elderly subject to burns at lower temperatures.

Thermostats Poorly Control Outgoing Water Temperature

Many homeowners and unwitting contractors reasonably assume that the thermostat setting is an accurate proxy of outgoing water temperature. While it is true that higher thermostat settings yield higher average temperatures, averages are less meaningful when the temperature variation is large.

Thermal stratification—also known as thermal stacking—yields hotter water at the top of the tank compared to the bottom [4]. Sometimes the temperature difference can be as much as 15 to 30 degrees. As demand pulls hot water from the top of the tank, inlet supply pressure forces cold water to the tank bottom via the internal dip tube. This directs cold water closest to the heating element for best heating efficiency. Rising heat forces more buoyant hot water (hence more heat) to the top of the tank, while cooler incoming water fills the bottom. Frequent bursts of hot-water demand—such as turning a faucet on and off several times, or a washing machine cycling—cause sequential inrushes of cold water, shocking the thermostat into a secondary heating cycle.

Since most thermostats measure temperature at the bottom of the tank, when water at the top is already at the target temperature, this extra cycling causes the peak hot-water temperature to rise even higher than the 120°F thermostat setting. Furthermore, ANSI standard Z21.10.1-2013 permits a ±10°F variation in thermostat accuracy, with field engineers reporting even wider ranges [5]. In extreme cases, allowances for thermal stacking permit up to a 30-degree temperature rise above the target thermostat setting. As a result, even at a 120°F nominal setting, water heaters are capable of producing much hotter temperatures than expected. This variability subjects occupants to severe and unpredictable scald risk, even at a nominal 120ºF thermostat setting.

Cold-Shower Syndrome

The opposite condition also occurs, where thermostat hysteresis and standby heat losses yield water temperatures considerably colder than expected. Unlike a forced-air furnace, where the air temperature remains within a few degrees of the target thermostat setting, water-heater thermostats have a very wide hysteresis range between on/off trip points. This range—as wide as 20-30 degrees—eliminates rapid cycling and excessive energy loss. This means that although the thermostat setting reads 120ºF, the actual tank water temperature could drop as low as 90-100ºF after several hours of non-use—particularly overnight when air temperatures are lowest. The tank water temperature will continue to decay until such time that standby losses cause the temperature to fall below the minimum thermostat trip point, or until a sudden demand for hot water causes an inrush of cold water, signaling the thermostat to trigger a new heating cycle.

A typical comfortable range for a shower at the point of use is 105-110ºF. Due to thermal losses between the water heater and the shower head, a two-to-five-degree temperature loss along the pipe is typical. Therefore, to enjoy a shower at 108ºF, the minimum acceptable temperature at the water heater outlet should be at least 110-113ºF, assuming no cold-water mixing. Given the foregoing discussion, it stands to reason that even were the thermostat set to 120ºF, the actual water temperature at the shower head could be as low as 90-95ºF—well below an acceptable temperature for a satisfying shower. It's no wonder that many consumers complain of cold showers, concluding that their tank or thermostat is defective.

Quad-Channel Temperature Logger

Figure 4. Extech SDL200 4-Channel Temperature Meter and Data Logger. Logging interval set to 10-seconds for 48+ hours captured essential data for forensic analysis.

Forensic Analysis Using Multi-Channel Loggers—It's in the Data

Despite the homeowner's predisposition to fault the water heater, Buildera approached this investigation without bias as to the potential problem(s). Rather, impartial scientific methods using multi-channel temperature loggers guided all measurements and documentation. While a simple fix could have been to raise the dial temperature and see what happened, this would have obfuscated the underlying cause and effect, as well as increasing unintentional scalding.

Performing Baseline Temperature Measurements

When Buildera first tested the water temperature using an immersion thermocouple (Fluke® 80PK-22 or similar) at various faucets, the hot-water temperature measured between 113-119ºF, which was within the expected range after accounting for thermal loss between the heater and faucet. In order to flush out tepid water within the pipes, water flowed freely until the temperature stabilized near its maximum. This indicated that, at the time of baseline measurements, the water heater was capable of producing sufficiently hot water for a satisfying shower. However, such measurements were insufficient to understand how the water temperature varied throughout the day with different demand loads and, more particularly, why early-morning shower temperatures were far below minimum acceptable levels.

Considerations of Temperature Data Logging

To assess overall temperature patterns, Buildera deployed the Extech® SDL200 4-Channel Temperature Meter in Figure 4 for its multi-channel capability and removable SD memory card, simplifying data export to an Apple® MacBook Air®. Tests were conducted over a two-day period between May 25-27, 2013 using various Type-K thermocouples optimized for the measurement task. Buildera assigned the temperature-logger channels as shown on the following table:

Channel	Thermocouple Label / Location	Expected Range
1	T[hot]—Hot-water pipe outlet temperature	90°-140°F
2	T[cold]—Cold-water pipe inlet temperature	55°-70°F
3	T[flue]—Outside-flue surface temperature	70°-300°F
4	T[ambient]—Utility closet ambient air temperature	55°-85°F

However, during the initial setup and validation, unexpected temperature offsets appeared across all thermocouple channels. A subsequent investigation revealed that, like many data loggers and acquisition systems, the SDL200 was susceptible to ground loops when measuring multiple thermocouples on a bonded system. This was due to small voltage offsets between each measurement node and non-isolated input amplifiers. True differential instrumentation input amplifiers are isolated from all other channels, including ground, helping to minimize channel interference and ground-induced noise.

To illustrate this point, Type-K thermocouples have a thermal sensitivity of 41 µV/°C. Therefore, even just 100 µV of voltage offset due to ground current differentials across a finite impedance caused several degrees of error in the displayed temperature measurement. Measuring the voltage difference between thermocouples with an Agilent (Keysight) U1273A DMM, virtually all of the measured error could be correlated to the voltage differentials seen between grounded sensors. Although the hot and cold-water pipes were already bonded together, installing an additional heavy-gauge copper bonding wire between measurement points reduced the impedance and offset errors slightly, but not enough to justify a best practice.

To mitigate measurement errors, Buildera re-mounted all but one thermocouple using a thin insulating layer of Kapton® polyimide tape. This step electrically isolated each thermocouple from the effects of grounding and bonding. The thin-tape layer did not materially affect the temperature measurement accuracy of the target surface, and it eliminated all ground loops between sensors. Although non-grounded thermocouples are available, their thermal response times are typically slower due to the mechanical isolation of the sensor and its housing.

In collaboration with Onset Computer Corporation, Buildera subsequently Beta tested and ultimately switched future field measurements to a production version of the Onset HOBO UX120-014M Quad Thermocouple Data Logger (Figure 5), which offered improved measurement accuracy, as well as significantly longer battery life suitable for extended temperature studies lasting weeks or months. Regardless of logger choice, the user must always test for ground-loop errors and electrically isolate each measurement node if necessary.

Onset® UX120-014M Quad Logger

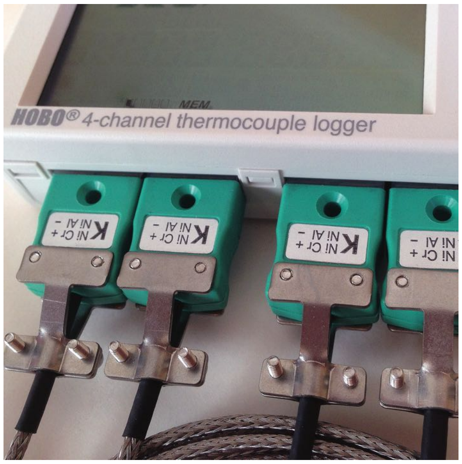


Figure 5. The UX120-014M provides four dedicated thermocouple channels and an internal ambient temperature sensor.

Hot Water Outlet Temperature Measurement—T[hot]

A Buildera ThermaDur™ Type-K pipe-clamp surface thermocouple such as shown in Figure 6 was installed around the 3/4″ copper pipe hot water outlet, approximately 1″ from the top of the water heater. Pipe insulation was removed during thermocouple installation and reinstalled to minimize ambient-temperature influence on the hot-water outlet measurement. Due to the high thermal conductivity and fast response time of copper pipe, the exterior pipe-surface temperature approximated the actual water temperature, which Buildera validated with independent water-temperature measurements drawn from the source.

Buildera ThermaDur™ Thermocouple

Figure 6. Buildera ThermaDur™ Type-K Pipe Thermocouple features a hose clamp, integrated temperature sensor, and protective stainless-steel sheath ideal for cost-effective pipe temperature measurements and forensic studies.

Measuring Flue Temperature

Figure 7. Measuring flue temperature T[flue] with a Fluke® 80PK-11 strap-on type-K thermocouple provides an accurate indicator of thermostat on/off cycling.

Figure 8 (below). Water-heater measurements over a 48-hour period compare temperatures of hot water (orange), cold water (blue), exhaust flue (dashed red), and ambient air (green). Hot-water use during a firing cycle typically extended the heating cycle 20 to 40 minutes. Graph produced with Plotly (www.plot.ly). For interactive graph, go to website: https://plot.ly/~glowitz/1

Cold Water Inlet Temperature Measurement—T[cold]

Similarly, Buildera installed a second thermocouple around the 3/4” cold-water copper inlet, approximately 12” from the top of the water heater. Care was taken to avoid mounting the thermocouple near the exhaust flue, which could adversely corrupt temperature readings. The rationale for measuring the cold water supply was to confirm that the incoming temperature was low enough to trigger the thermostat after a sufficient cold-water inrush.

Flue Temperature Measurement—T[flue]

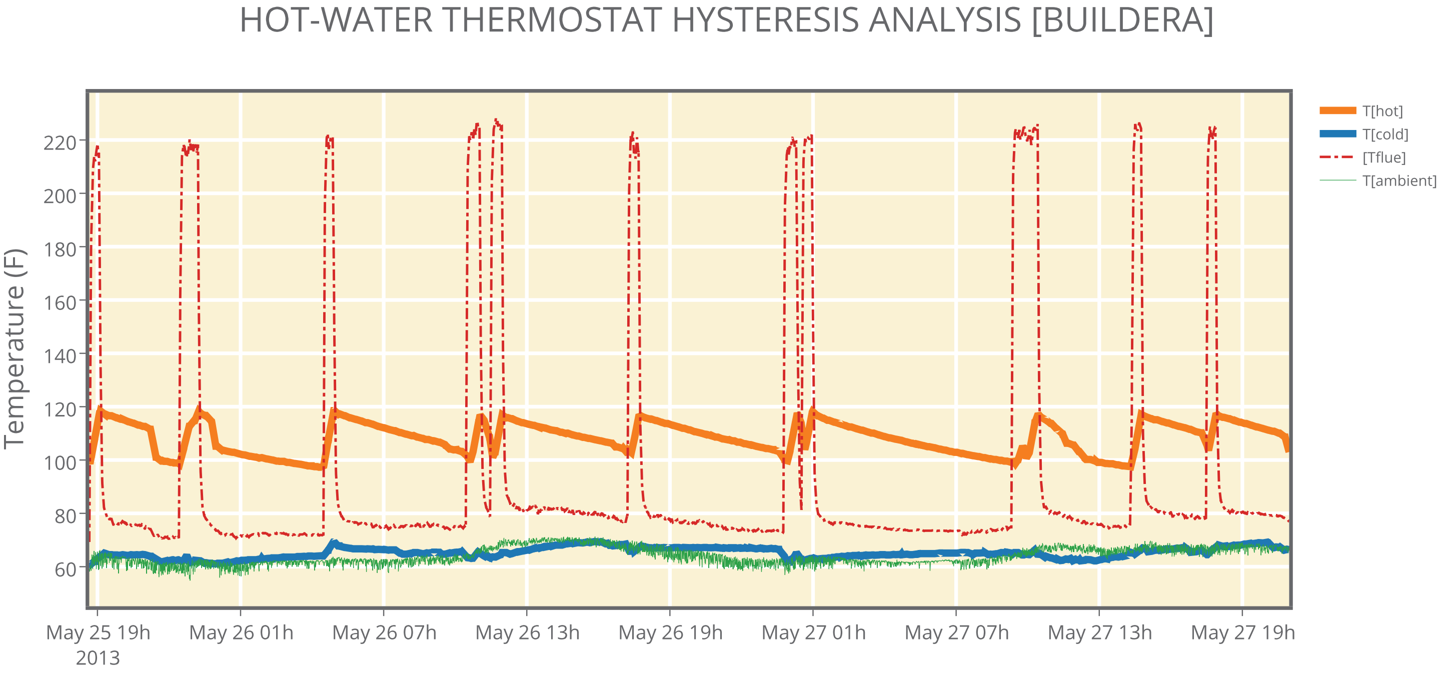
Buildera deployed a Fluke® 80PK-11 Type-K Velcro® Thermocouple around the gas flue to non-invasively measure the external flue temperature. The thermocouple was placed on the water-heater vent approximately 6” above the flue outlet. This measurement provided a consistent proxy for thermostat activation. Upon firing, the flue surface temperature increased nearly instantaneously, rising to 220°F or thereabouts. Upon reaching the high trip point, the thermostat closed the gas valve. The flue temperature then dropped precipitously, providing a reliable indicator of the thermostat switch-off point. Performing low-pass filtering and thresholding of the data prior to taking the mathematical derivative of the flue temperature provided very accurate markers of step changes in temperature. The time delay between adjacent spikes indicated the duration of the heating cycle, which could be later converted into a binary on/off plot versus time.

Ambient Air Temperature Measurement—T[ambient]

Buildera adhered a type-K bead thermocouple to a nearby wall to measure ambient air, which was useful to understand air-temperature influence on thermostat operation.

Discussion of Measurement Results

As shown in the lower Plotly graph of Figure 8, temperature readings continued for two days with the following observations:



Thermostat Hysteresis

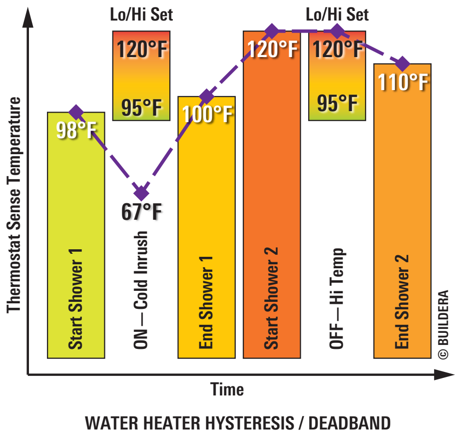


Figure 9. Water heater deadband chart illustrates the thermostat temperature profile vs. time and shower demand. Chart adapted with permission from Buell Inspections, Seattle, WA [6].

- The thermostat cycled 4-6 times/day for a duration of 20 to 60 minutes per cycle
- Ambient-air temperature inside the utility closet varied from 60°-71°F
- After periods of non-use, such as five or more hours, the hot-water temperature decayed approximately 2.3°-2.6°F/hour to 97°-103°F degrees—above the minimum threshold to trigger the thermostat before the next morning use
- Upon first use in the morning, shower temperature at the head was in the 95°-101°F range, well below acceptable minimums
- After sufficient inrush of cold water, the thermostat switched on, triggering a heating cycle with a temperature rise between 0.3°-0.8°F/minute, depending on demand during recovery
- The temperature rise was gradual, lasting from 20 to 60 minutes
- Given a typical shower duration of 8-10 minutes, there was insufficient heat rise during the first shower to provide a satisfying temperature
- As shown in Figure 9, at such point when a second occupant took a morning shower, there was an ample supply of hot water due to earlier thermostat activation
- Data was collected during late May when ambient temperatures were relatively warmer

According to the laws of thermodynamics, were the ambient air temperature much lower (larger differential between air and tank temperature), such as during the winter, the water heater would lose heat more rapidly during the night, thereby triggering the thermostat early in the morning, prior to the first shower—explaining why morning showers in winter were paradoxically hotter than showers in warmer months.

Solutions

Armed with forensic knowledge, remedies were more evident. One solution raised the thermostat temperature, such that the low trip point was at least hot enough for a comfortable first shower. Using Figure 8 as a guide to establish the new threshold, a 10°F increase in thermostat setting to 130°F would raise the minimum hot-water output to 107-113°F—a more suitable shower temperature. Indeed, after increasing the thermostat high trip point to 130°F, the homeowner experienced comfortable showers, even during first use. However, this solution also raised the risk of scalding due to higher overall temperatures and stacking effects.

Furthermore, this boost also consumed more energy over a 24-hour period when, in practice, the hotter water was only required in the morning or after several hours had elapsed without hot-water consumption. Hotter water could also reduce tank life due to higher thermal expansion, as well as accelerate mineral deposits and scale. Given the increased scalding risk and higher energy demand, this solution was only a temporary fix to the cold-shower dilemma.

Recirculating Pump

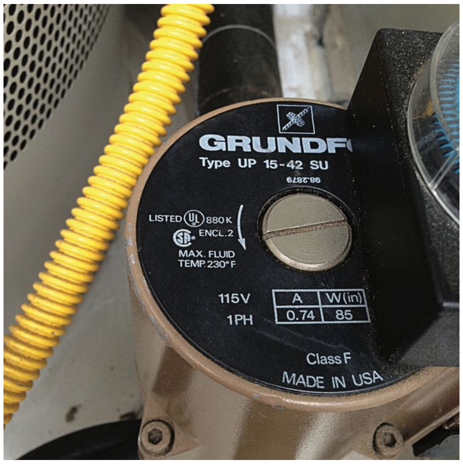


Figure 10. A timer connected to the Grundfos pump shocked the water-heater thermostat into a firing cycle prior to the first shower, raising the water temperature to a minimum acceptable level.

Recirculating Pump to the Rescue

As noted previously, the system also included a 1/2" recirculating line and Grundfos pump. The owner had previously deactivated the recirculating system due to concerns about premature copper-pipe erosion, incremental energy consumption from recirculating losses, and the electricity to run the pump.

To mitigate these concerns, the recirculating pump offered a practical method to trigger the thermostat with negligible impact on energy use. Tepid water in the return line approached ambient-air temperature overnight, shocking the thermostat into a heating cycle. Upon programming the pump timer, the thermostat was reset back to 120°F. Automatically activating the pump for just a few minutes at 5:30 AM forced the cooler water in the return line to trip the thermostat, thereby reheating the water. By the time the first occupant took a morning shower, the hot-water supply had already reached its target 120°F limit. This provided ample hot water for at least two back-to-back showers.

Further Improvements

While this last approach provided a viable remedy, it relied on synchronization of the pump schedule with the occupants. Furthermore, it still left the hot-water loop vulnerable to breeding harmful bacteria, such as Legionella. The ultimate solution to this dilemma was to sacrifice some energy efficiency in exchange for an increase in tank temperature to 135-140°F, sufficient to kill bacteria. To avoid scalding, however, an ASSE-approved temperature-compensating mixing value must be installed just after the hot-water outlet by mixing with cold water. This way, the tank could remain at a safe temperature from a bacteria standpoint, while the 120°F output mitigated scalding risk.

This offered the added benefit of slower hot-water depletion during a shower, since the tank had a heat capacity reserve well in excess of the target temperature. Although this approach was less energy efficient due to increased standby losses and subsequent mixing losses, it ensured the occupants an ample supply of hot water regardless of season or time of day. Note, however, that Legionella can remain active at temperatures up to 122°F, hence ASHRAE now recommends no less than 124°F throughout the hot-water supply and return. Given these hotter temperatures, anti-scald faucets and mixing valves are essential safety measures at the point of use.

Conclusion

Through scientific methodology and analysis using multi-channel temperature loggers, Buildera resolved frustration over cold showers that had plagued the homeowner for years. An improved understanding of the temperature profile over time yielded reasonable solutions that balanced opposing demands of hot showers and energy efficiency. Increasing the thermostat setting approximately 10°F to 130°F ensured sufficient hot water throughout the year. Reactivating the existing recirculating line in the morning was an alternative option. During the analysis, other observations and improvements were noted to mitigate bacteria build-up while preventing scalding at the point of use, including the addition of a temperature-compensating mixing valve at the water heater output, coupled with anti-scald fixtures at the point of use.

About the Author

Greg Lowitz is the Founder and CEO of Buildera — a global provider of engineering-forensic tools, environmental data logging, and consulting services for professionals and homeowners. He holds Bachelor's and Master's degrees in electrical engineering from Stanford University.

The author welcomes your feedback and insights. Please direct all inquiries, suggestions, and corrections regarding this application note to greg.lowitz@buildera.com.

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Notices

Buildera provides this application note for informational purposes only and makes no warranty express or implied. Each situation is unique and may require different approaches to resolving domestic hot water issues and consumer complaints. Hot water research, safety, and best practices continue to evolve and readers may encounter conflicting advice. Always check current building codes prior to construction, remodeling, or repairs.