School HVAC

Rethinking School Potable Water Heating Systems

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Results of several recent field tests, and of ongoing hot water piping system laboratory tests being performed by the author, have shown that the conventional way of designing and operating school water heating systems is wasting tremendous amounts of energy, resulting in water heating system operating costs much higher than they could and should be.

This article describes results from potable water heating system field tests in two schools and provides recommendations on alternative school water heating system designs and operating practices that significantly reduce operating costs and have considerably lower first cost. Projected payback periods usually are instantaneous in new construction and often attractive in retrofits, especially if an existing tank needs replacement.

One of the most common practices in school water heating system design is to serve multiple fixtures from a central location through the use of one or more hot water recirculation-loop (RL) systems. In RL systems, two hot water lines are provided to the approximate vicinity of each fixture, one a supply line, the other a return line. A pump is used to circulate hot water to the fixtures, and then back to the central water heater through the return line, so that the lines are hot throughout the portion of the day when hot water is needed. This means hot water is available quickly to each fixture. Analysis and field test data show that heat loss and pumping energy in RL systems usually is extremely high compared to the loads served, significantly increasing energy use beyond the energy used at the fixtures.

Analytical work, verified by actual field tests in schools, and separate laboratory testing, has shown that school potable water heating system energy use can be significantly reduced by altering operational practices at a minimum

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(school water heating systems have no water draws close to 80% of the time, which creates opportunities for energy savings).

In addition, system energy use can be reduced significantly by changing system design practices to reduce RL system length or eliminate RL systems entirely. This can be accomplished by rethinking locations of hot water using fixtures, and using a greater number of smaller water heaters located closer to fixtures. Energy use reductions of a minimum of around 50% typically are cost effective (usually with instantaneous payback periods in new construction because of lower first cost), with some installations saving in excess of 90%.

Methodology

Analysis using standard piping heat loss calculation procedures, such as shown in the *1972 ASHRAE Handbook—Fundamentals,*[1] and standard heat transfer textbooks suggested that even relatively short piping runs, such as those as short as 20 ft (6.2 m), result in significant energy waste, even if heavily insulated. Moreover, this energy loss increases considerably when such lines are kept hot much of the time as they are in RL systems.

Analysis furthermore indicated that use of multiple water heaters located relatively close to fixtures could reduce piping heat loss significantly. This was true for both tank-type and tankless water heaters because even tank-type water heaters have low standby heat loss compared to piping systems (even well-insulated ones) that are hot much of the time. This is especially true of electric water heaters, which have very low heat loss rates because they do not have flue and/or heat exchanger heat losses.

To determine whether the analytical predictions were valid, field tests were performed on three separate water heating systems in two high schools.[2,3,4,5,6] Additionally, a series of laboratory tests on different hot water piping system layouts has been initiated by the author, enabling direct measurement of piping heat loss characteristics (UA factors) under a variety of conditions. Some results from the latter work are being reported in a symposium paper at the 2005 ASHRAE Annual Meeting (this paper will be available later this year in *ASHRAE Transactions* 111:[2]).[7]

Further analytical work using data and information from the field tests led to further refinements in recommended school water heating system design and operation, as described here.

Laboratory and Field Test Results

In the process of selecting field test sites, plumbing schematic drawings were reviewed for a number of elementary, junior and senior high schools. All of the school drawings revealed use of one or more hot water RL systems. The efforts reported here tested three separate hot water RL systems in two high schools in Tennessee. One monitored system served the cafeteria kitchen and many of the bathroom and classroom sinks.

At the other school, a second monitored RL system served only the cafeteria kitchen. At that same school, a third monitored RL system served a number of distributed lavatory and countertop sinks, several janitorial sinks, and a few infrequently used fixtures such as a private shower and a classroom clothes washing machine.

Significant findings from the school water heating system field tests, which probably apply to school water heating systems in general, were as follows:

- Schools are unoccupied approximately 50% of the year.

• Schools are unoccupied 50% to 70% of the hours during occupied days.

• Therefore, schools are unoccupied, with no hot water use at all, approximately 80% of all the hours in the year.

• Push-button pressure actuated automatic valves had a tendency to stick in the on position, wasting significant amounts of hot water.

• Bathroom and countertop sinks use small amounts of hot water (peak use typically less than 5 gallons [19 L] per day, with an average of typically less than 2 gallons [7.6 L] per day per sink) when results are corrected to remove stuck fixture draws.

• The major school hot water uses typically are the cafeteria kitchen and locker room shower facilities.

• The next major school hot water use is janitorial cleanup, occurring intermittently throughout the day, but mostly in afternoon and early evening hours.

• Fixtures that are spread most widely throughout the school usually are low-use fixtures such as sinks or occasional use fixtures such as private showers, or classroom clothes or dish washers.

An observation from the actual school field test sites, and from study of plumbing system layout drawings from several other schools, is that many of the distributed fixtures relatively easily could be plumbed to be served by individual water heaters centrally located relative to clusters of those fixtures. Moreover, slight changes to fixture locations could make it even easier to serve clusters of end uses with short runs from localized individual water heaters. Doing this would make it practical to eliminate RL piping.

In the third monitored RL system discussed previously, the natural gas-fired RL system was monitored for a period of time in the as-found condition (RL pump running continuously), then time-clock control of the RL pump was implemented and the system monitored further. Finally, the RL system was changed out for a set of three point-of-use (POU) electric resistance water heaters and monitored for the remainder of the test period. The total monitoring period was one calendar year.

The RL system had 425 ft (129 m) of 1 in. (25.4 mm) copper supply line, and 420 ft (128 m) of ½ in. (12.7 mm) copper return line, all insulated with ½ in. (12.7 mm) thick foam insulation.

Table 1 compares projected annual energy use and savings of the RL vs. POU field test. In the time-clock controlled RL portion of the test, the RL pump was turned off for six hours every night (the maximum period allowable given the diverse uses on the circuit). Time-clock controlled (RL controlled or RLC configuration) operation reduced projected annual energy use by approximately 14% relative to the initial continuously operating (RL uncontrolled or RLU) configuration. By comparison, the switch to POU resistance water heaters reduced projected annual water heating energy use by 91% and operating costs by around 75%.

Figure 1 compares the normalized annual energy use breakdown of all three configurations. The large energy savings of the POU configuration compared to the RLU configuration came from eliminating the RL piping heat loss, which represented approximately 75% to 80% of total energy use when tank heat input efficiency and pumping power to provide the RL heat loss were considered. In fact, the resistance POU system used about as much electric energy to do all of the water heating as just the pumps on the gas-fired RLU system.

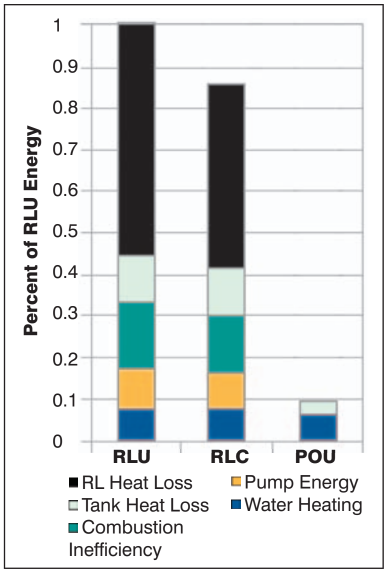

Figure 1: Energy use comparison.

Analysis of actual costs for the retrofit showed that the POU system would have been less expensive to install initially (less than half the cost) than the RL system, and that the retrofit would have been cost effective with around a five-year payback if it had been done at the time of a needed replacement of the gas water heater. The measured average piping heat loss rate (UA factor) on this RL circuit totaled about 0.15 Btu/h·ft·°F (0.26 W/m·°C). Heat loss from the piping can be estimated using the formula $Q = UA(T_{pipe} - T_{air})$, noting that T_{pipe} changes with length as heat is lost.

The two high school cafeteria kitchen water heating circuits monitored showed an average hot water use of 700 to 800 gallons/day (2650 – 3028 L/day) on days when school was in session and meals were being served, with peak use days of around 1,000 gallons/day (3785 L/day) and 1,300 gallons/day (4950 L/day) for the two schools. Moreover, hot water use in the kitchens (which served both breakfast and lunch in the higher peak use case) was concentrated from approximately 6 a.m. to 2 p.m., and was zero at all other times. This means that the kitchen water heating circuits sat idle at least 15 continuous hours per day.

Laboratory testing by the author on nominal ¾ in. (19 mm) and ½ in. (13 mm) diameter copper piping systems with various levels of insulation indicates that UA factors are as shown in *Table 2*.[8] These values are consistent with those calculated using standard heat transfer textbook correlations. The UA values for 1 in. (25.4 mm) nominal diameter copper pipe shown in *Table 3* are estimated from the ¾ in. (19 mm) nominal diameter laboratory data, and will be updated when laboratory testing is complete.

Recommended Design and Operating Strategies

Conclusions from the analytical work and testing performed lead to the following design recommendations for school water heating systems.

Plumbing System Layout

Greater attention should be paid to minimizing the total length of hot water distribution piping, especially distance to farthest fixtures from the water heater(s). It may be possible to eliminate the need for RL piping by relocating the water heater(s) more centrally relative to the fixtures. Doing so would result in shorter one-way distances from tank to fixture, which may reduce hot water delivery delay time and water waste to levels that negate the need for the RL system.

In addition to centralizing water heater location relative to the fixtures served, changes in fixture locations similarly can reduce hot water piping lengths. For example, placing classroom sinks in adjacent corners of multiple classrooms, to all be served by a nearby water heater, can significantly reduce hot water piping length compared to placing sinks at opposite corners of those same rooms.

Use POU Water Heaters

The high heat loss from RL piping makes it desirable in most school designs to use multiple POU water heaters instead of RL systems. Standby heat loss from water heater tanks, which typically are well-insulated, is small compared to piping heat losses, even when the piping is well-insulated. *Table 3* gives a comparison of representative piping heat losses for various pipe sizes with good insulation (¾ in. [19 mm] thick foam), assuming zero-flow UA values from *Table 2* for a conservative estimate of piping heat loss. *Table 4* gives a comparison of typical tank heat loss (UA) factors,[9] and representative hourly and daily heat loss rates for several types of tank-type water heaters.

Comparing *Tables 3* and *4*, we see that for a 1 in. (25.4 mm) nominal diameter RL loop (typical of a size that might be used in a school), RL piping heat loss, even controlled so that the RL loop is hot only eight hours/day, exceeds heat loss from the best resistance tank shown when the pipe length is more than a mere 20 ft (6 m). Note moreover, that the RL system has both supply and return piping. Assuming 1 in. (25.4 mm) nominal diameter supply piping and ½ in. (13 mm) return piping, this means a fixture distance from the water heater that is greater than about 12 ft (3 m).

This is one of the reasons high-efficiency resistance water heaters are attractive options for distributed POU water heaters on low use loads. Moreover, piping heat loss exceeds tank heat loss from even the lowest efficiency fossil-fired water heater shown (a minimum efficiency fossil-fired water heater with a standing pilot) when the piping length is more than about 223 ft (68 m). With 1 in. (25.4 mm) supply and ½ in. (13 mm) return lines, this corresponds to a fixture distance from the water heater of about 136 ft (41 m). The total RL piping length in a typical school usually far exceeds even the 223 ft (68 m) value.

For example, for the high school POU before vs. after retrofit field test site discussed previously, the total RL length was 845 ft (257 m). In schools where all fixtures are served by a single large RL loop, RL piping lengths greater than 1,000 to 2,000 feet (300 to 600 m) are not uncommon.

System	Gas MMBtu kWh	Electricity kWh	Total Gas + Elec. kWh	Savings
RLU	91.3 (26,740)	2,614	29,354	0%
RLC	78.2 (22,903)	2,402	25,305	14%
POU	0	2,788	2,788	91%

Table 1: RL vs. POU before vs. after field test comparison.

Nominal Pipe Size in. (mm)	Foam Insul. Thickness in. (mm)	Zero Flow UA Btu/h · ft · °F (W/m °C)	Asymptotic High-Flow UA Btu/h · ft · °F (W/m °C)
½ (13)	0	0.226 (0.39)	0.36 (0.62)
½ (13)	½ (13)	0.128 (0.22)	0.20 (0.35)
½ (13)	¾ (19)	0.116 (0.20)	0.19 (0.33)
¾ (19)	0	0.388 (0.67)	0.44 (0.76)
¾ (19)	½ (13)	0.150 (0.26)	0.25 (0.43)
¾ (19)	¾ (19)	0.142 (0.25)	0.24 (0.42)

Table 2: Copper piping heat loss rate (UA) summary.

Effective standby heat losses for tankless water heaters typically are less than for tank-type water heaters but are not zero because of the heat lost from the mass of the heat exchanger and water contained within it after each firing. This heat loss behaves somewhat like standby heat loss from tank-type water heaters, but is proportional to the number of firing cycles rather than the amount of standby time. Since the number of firing cycles would be low during school idle periods, standby heat loss also would be low.

Best choices for what kinds, tank sizes, and heating rates to be used in POU water heaters varies with the loads being served. For low-use loads such as sinks and occasional use fixtures, high-efficiency electric resistance water heaters, with their low standby heat loss, low first cost, and easy installation are probably the most cost-effective and energy-efficient choice. For larger loads such as dispersed janitorial sinks, electric resistance, heat pump water heater (HPWH), or fossil-fired water heaters should be evaluated.

For still larger loads such as cafeteria kitchens or locker room shower facilities, HPWH or fossil-fired water heaters probably are the most cost-effective options. Note, however, that sizing of HPWHs,[10,11] should be done differently than for fossil-fired units. Due to the higher first cost per unit of heating capacity for HPWHs compared to other types of water heaters, best designs usually have a relatively small HPWH coupled with fairly large storage tanks, such that HPWH run-time averages at least 75%. The most common mistake in HPWH system designs is oversizing the HPWH. Note that the installed cost of multiple POU water heaters is usually substantially lower than the installed cost of lengthy hot water supply and return lines in RL systems. With pumps eliminated, maintenance costs also are usually lower.

A special note on types of fossil-fired water heaters to use is in order for RL and POU applications. Due to the prolonged idle times in school applications, the best operating strategy is to completely turn off the water heater after the last hot water use of each day, and to re-enable the water heater slightly before the next hot water use. Doing this reduces tank standby heat loss as well as piping heat loss by letting the tank cool down during non-draw periods.

(T_{hot} = 135°F, T_{air} = 67.5°F) (T_{hot} = 57°C, T_{air} = 20°C) Assumes ¾ in. (19 mm) thick foam insulation				
Nominal Pipe Size Copper in. (mm)	**UA Btu/h · ft · °F (W/m °C)**	**Heat Loss Btu/h · ft (W/m)**	**Heat Loss 100 ft (30 m) Hot 24 h/day Btu/day (Wh/day)**	**Heat Loss 100 ft (30 m) Hot 8 h/day* Btu/day (Wh/day)**
½ (13)	0.116 (0.20)	7.8 (9.3)	18,792 (5,506)	7,054 (2,067)
¾ (19)	0.142 (0.25)	9.6 (11.3)	23,040 (6,751)	9,247 (2,709)
1 (25.4)	0.157 (0.27)**	10.6 (12.5)**	25,440 (7,454)**	11,096 (3,251)**

* Includes energy for one piping system reheat per day.
** Estimated from ¾ in. (19 mm) data.

Table 3: Pipe heat loss comparison.

It is important to avoid using fossil-fired water heaters having standing pilot lights and any that require a continuously operating circulating pump. Using fossil-fired water heaters that have pilotless ignition allows them to be activated and deactivated by conventional time-clock controls, or by more sophisticated building energy management systems.

Tankless water heaters, both electric and fossil-fired, are worth examining in most school applications. In some cases the higher first cost and possibly higher maintenance costs of the tankless water heaters are economically justified, while in other cases they are not. In most cases the heating rate required for tankless water heaters to serve loads is substantially higher than that necessary for tank-type units serving the same loads, which is a significant issue for electric resistance tankless water heaters and for fossil water heaters serving high-draw rate loads. If the total amount of hot water used on a circuit is low but peak flow rates are high, tankless water heaters are probably not economically justified for that circuit compared to a tank-type water heater.

Note that tank-type POU water heaters that serve sink loads can be quite small and need only low heat input rates (and, therefore, low power requirements). POU water tank sizes for such applications need only be 2 to 5 gallons (7.6 to 19 L), with heating rates less than 1,000 W, such that operation of resistance units on 110 V, 15 amp circuits is practical. Moreover, with the exception of the locker room shower and cafeteria loads, most other school water heating loads can be served by residential sized water heaters, needing tank sizes of 50 gallons (190 L) or less (80 to 100 gallons [300 to 400 L] if operated in an off-peak fashion that limits heating to nighttime hours), and heating rates of 4,500 W or less (often needing less than 1,000 W). Similarly low heating rates can be used on tank-type fossil-fired water heaters in such applications.

The author has had discussions with most water heater manufacturers, which have confirmed that the most common type of electric resistance water heaters (having nothing more than simple mechanical thermostats and resistance elements), can be safely run on voltages lower than their nameplate rating. The only consequence is that amperage and power rating drop at lower voltages.

Heating rate is proportional to the square of the voltage ratio from nameplate, such that an element having a 4,500 W rating at 230 V (thus, drawing 20 amps) will have a 110 V heating rate of $(4{,}500) \times (110/230)^2 = 1{,}029$ W (thus, drawing 9.4 amps). Some manufacturers show dual-voltage ratings on their water heaters to make this ability clear.

This fact is useful, for it means that there is ready availability of resistance water heaters that can be run on 110 V if desired, which may negate the need for special 230 V wiring to the water heaters. They may perform adequately on existing 110 V, 15 amp circuits. However, that electric resistance water heaters should *not* be operated on voltages *above* their nameplate ratings unless permitted by the manufacturer and should not be operated on lower than nameplate voltages if they contain any electronic controls, motors, pumps, fans, relays, or other non-resistance load items.

System Operating and Control Strategies

Regardless of whether POU water heating systems or more conventional fossil-fired RL systems are used, the best water heating system operational strategies for schools minimize the amount of time piping and tanks are hot. This is because the tanks and piping are idle most hours of the year.

With RL systems, at a minimum the RL pumps should be turned off after the typical time of last draw of the day, and turned back on slightly before the time of anticipated next hot water draw. Due to the long no-draw periods in school applications, this RL loop off-time will typically be a minimum of six hours (overnight), and may be many months (summer break). However, natural convection heat loss from the tank into the cool piping of a RL system or into the incoming cold water line sometimes can negate savings from turning the RL pump off. Making sure inlet and outlet piping of the tank are equipped with heat traps of some sort will reduce the amount of natural convection heat loss from the tank that can occur.

A more desirable operating strategy is to turn off both the RL pump and the heat input to the tanks when hot water is not needed, such that the tanks cool off as well as the piping. Most tank-type fossil-fired water heaters can fully reheat in less than one hour, and commercial fossil-fired water heaters, which have higher heating rate-to-tank-volume ratios, often can reheat much faster.

Similarly, electric resistance water heaters usually can provide an adequate amount of hot water for early use within 15 minutes of a cold start if a dual-element tank is used because the upper element heats the top part of the tank quickly. This means that water heaters only need to be reactivated within 15 to 60 minutes of an anticipated need for hot water.

Note that fossil-fired water heaters with pilotless ignition and non-continuous pump operation should be used to maximize tank deactivation capabilities and simplify deactivation control through timers or more sophisticated controls, such as through building energy management systems. Electric units inherently lend themselves to such control. Simple seven-day programmable timers that control water heaters and/or RL pumps can cost only a few hundred dollars installed and typically have retrofit payback periods of six months or less. In schools, deactivation of tanks during idle periods is desirable whether POU or central water heaters are used.

(T_{hot} = 135°F, T_{air} = 67.5°F) (T_{hot} = 57°C, T_{air} = 20°C)								
Type	Input Efficiency	Energy Factor	UA Btu/h · °F (W/C)		BTU/h (W)		Btu/Day (Wh/day)	
Resistance	100	0.86	4.125	(2.18)	278	(81.5)	6,683	(1,958)
Resistance	100	0.90	2.815	(1.48)	190	(55.7)	4,560	(1,336)
Resistance	100	0.95	1.333	(0.70)	90	(26.4)	2,159	(633)
Fossil-Fired	80	0.54	15.25	(8.04)	1,029	(301)	24,705	(7,239)
Fossil-Fired	80	0.59	11.27	(5.94)	761	(223)	18,262	(5,351)
Fossil-Fired	85	0.72	5.38	(2.84)	363	(106.4)	8,720	(2,555)
Fossil-Fired	96	0.86	2.79	(1.47)	188	(55.1)	4,520	(1,324)

Note: Results vary with energy factor (EF) rating, not tank size, but EF varies with tank size.

Table 4: Tank heat loss comparison.

A Note on *Legionella*

An issue that is sometimes a concern, especially in RL systems having extensive piping runs with idle side-branch circuits, is potential growth of *Legionella* bacteria and other pathogens in the water heating system. This is cause for concern most notably where persons with compromised immune systems will be exposed to aerosolized water containing the pathogens, such as in hospitals and elder care facilities. Optimal growth temperatures for *Legionella* and many other pathogens are from 70°F to 110°F (21°C to 43°C).

Deactivating RL systems for prolonged periods will drop them to ambient temperature, which, if warm enough, may enable growth of such microorganisms in the plumbing system. Note that under prolonged shutdown, the hot and cold water plumbing essentially would be the same temperature, so microorganisms can grow equally well in both hot and cold water plumbing—their growth is not limited to just the hot water lines. It may be advisable to perform a precautionary flush of the piping system after prolonged periods of non-use. In particular, the

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hot water plumbing can be subjected to a high-temperature flush of the piping system and all of its branch circuits after a prolonged period of shutdown. Readers should examine ASHRAE literature[12] for more information on this subject.

Use of well-designed POU water heater circuits in lieu of RL systems should reduce the potential for biological growth, such that they would behave similarly to typical residential water heating systems. Performing a high temperature flush of each water heating system after a prolonged period of shutdown is a relatively simple and inexpensive precaution for POU systems as well as for RL systems.

Conclusions

Analysis predicted, and laboratory and field tests have confirmed that schools should, for the most part, use multiple POU or near POU water heaters instead of hot water recirculation-loop piping systems served by centralized water heaters. Moreover, from an energy savings perspective, the water heating system, including piping and tanks, should be deactivated and allowed to cool during unoccupied periods, which are common in schools.

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