Related Commercial Resources

CHAPTER 51. SERVICE WATER HEATING

WATER HEATING energy use is second only to space conditioning in most residential buildings, and is also significant in many commercial and industrial settings. In some climates and applications, water heating is the largest energy use in a building. Moreover, quick availability of adequate amounts of hot water is an important factor in user satisfaction. Both water and energy waste can be significant in poorly designed service water-heating systems: from over- or undersizing pipes and equipment, from poor building layout, and from poor system design and operating strategies. Good service water-heating system design and operating practices will reduce operating costs and can often reduce first costs. The information in this chapter is thus critical for the sustainable design and operation of many buildings.

Research documenting hot-water use in modern systems is limited to certain segments. Some of the data in this chapter on hot-water demands for some types of buildings, applications, and fixtures may be outdated. Nevertheless, these data are provided for guidance, because they are often still the best available; however, these demand values are not intended for use as designers' sole references for hot-water system sizing purposes.

1. SYSTEM ELEMENTS

A service water-heating system has (1) one or more heat energy sources, (2) heat transfer equipment, (3) a distribution system, and (4) end-use fixtures.

Heat energy sources may be (1) fuel combustion; (2) electrical conversion; (3) solar energy; (4) geothermal, air, or other environmental energy; and/or (5) recovered waste heat from sources such as flue gases, ventilation and air-conditioning systems, refrigeration cycles, and process waste discharge.

Heat transfer equipment is direct, indirect, or a combination of the two. For direct equipment, heat is derived from combustion of fuel or direct conversion of electrical energy into heat and is applied within the water-heating equipment. For indirect heat transfer equipment, heat energy is developed from remote heat sources (e.g., boilers; solar energy collection; air, geothermal, or other environmental source; cogeneration; refrigeration; waste heat) and is then transferred to the water in a separate piece of equipment. Storage tanks may be part of or associated with either type of heat transfer equipment.

Distribution systems transport hot water produced by water-heating equipment to end-use fixtures. For locations where constant supply temperatures are desired, circulation piping or a means of heat maintenance must be provided.

End-use fixtures are plumbing faucets, accessories, and equipment requiring hot water that may have periods of irregular flow, constant flow, and no flow. These patterns and their related water usage vary with different buildings, process applications, and personal preference. Examples of end-use accessories are prerinse spray valves, faucet aerators, showerheads, wash down sprayers, and hose bibbs. Examples of end-use equipment are dishwashers, clothes washers, and pressure washers.

2. WATER-HEATING TERMINOLOGY

Distribution system efficiency. Heat contained in the water at points of use divided by heat delivered at the heater outlet during flow periods.

Energy factor. The delivered efficiency of a residential water heater when operated as specified in U.S. Department of Energy (DOE) test procedures (DOE 2001). See also ASHRAE *Standard* 118.2. The DOE significantly altered and updated residential and residential-duty commercial water heater testing and rating procedures in 2014 to 2016, so the procedures now apply to a larger array of different types and sizes of water heaters. As of late 2016 the **energy factor (EF)** rating has been superseded by a new rating: uniform energy factor, discussed later. The EF testing procedure and rating only used one hot-water draw pattern meant to approximate whole-house hot-water use, and hence could not be used for water heaters not meant for whole-house applications.

First-hour rating. An indicator of the maximum amount of hot water a residential water heater can supply in 1 h when starting with a tank that is up to temperature. This rating is used by the U.S. Federal Trade Commission (FTC) for comparative purposes and by the U.S. Department of Energy (DOE) for selecting the appropriate draw profile when testing for the uniform energy factor. Because peak draws taken over periods less than 1 h frequently drive residential equipment sizing, first-hour rating alone should not be used for equipment sizing. As for larger systems, storage tank volume and heating rate also play important roles.

Fixture unit. A number, on an arbitrarily chosen scale, that expresses the load-producing effects on the system of different kinds of fixtures. Fixture units have no units of measurement and are only meant for use when multiple fixtures are present.

Grid-interactive water heater. A water heater that both sends and receives signals from a central control point (e.g. the local electricity distributor), allowing the central control point (the electrical supply grid) to control how and when the appliance operates. Grid-interactive water heaters are incorporated into the electricity grid controls to help optimize and stabilize grid operations.

Heat trap. A device to counteract the natural convection of heated water in a vertical pipe. Commercially available heat traps for large equipment are generally 360° loops of tubing; heat traps can also be constructed of pipes connected to the water heater (inlet or outlet) that direct flow downward before connecting to the vertical supply or hot-water distribution system. Tubing or piping heat traps should have a loop diameter or length of downward piping of at least 300 mm. Various prefabricated check-valve-like heat traps are available for residential-sized equipment, using balls, flexible flaps, or moving disks.

Input efficiency. Heat entering water in the heating device divided by energy input to the heating unit over a specific period of steady-state conditions, or while heating from cold to hot, depending on how stated (steady-state versus average input efficiency); it does not include heat losses from the water heater jacket and/or tank. When used with fossil-fuel-fired equipment, this is commonly called **combustion efficiency**.

Maximum flow rate. Under the uniform energy factor (UEF) test procedure, for water heaters that are flow activated (e.g., tankless water heaters), a test is performed to determine the maximum flow rate of a device to be tested while meeting test temperature requirements and operating at maximum input rate, which is then used to determine the hot-water draw pattern to be used for testing.

Operating efficiency. Heat delivered at the heater outlet ($Q_{out} = mc_p[T_{hot\ out} - T_{cold\ in}]$) divided by heat input to the heating unit (includes heat losses from water heater jacket and/or tank) for any selected period for systems without recirculation pumps. For distribution systems with recirculation pumps, heat losses include recirculation line losses, because hot water at a reduced temperature is returned back to the heater. Thus, operating efficiency equals the heat delivered to the middle of the distribution line ($Q_{out} = mc_p\ [(T_{hot\ out} + T_{hot\ return})/2 - T_{cold\ in}]$) divided by heat input to heating unit. The operating efficiency of water heaters in systems with continuous recirculation can be further reduced by loss of stratification in storage heaters. Elevated return temperatures associated with continuous recirculation systems further reduce the operating efficiency of condensing water heaters (see Figures 1 and 2). This is also referred to the heater's real-world efficiency, which can be easily measured and used to estimate the energy use or operating cost. A system with higher operating efficiency may not always equate to a higher-performing system, because operating efficiency considers water temperature leaving the tank, not water temperature reaching the fixtures. A system with extremely long hot-water distribution piping and no recirculation may show a high operating efficiency, but hot water may never reach the farthest fixtures.

Overall system efficiency. Heat energy in the water delivered at points of use divided by the total energy supplied to the heater for any selected period.

Recovery efficiency. Heat absorbed by the water divided by heat input to the heating unit during the period that water temperature is raised from inlet temperature to final temperature (includes heat losses from water heater jacket and/or tank).

Recovery rate. The amount of hot water that a water heater can continually produce, usually reported as flow rate in litres per hour that can be maintained for a specified temperature rise through the water heater.

Standby loss. As applied to a tank water heater (under test conditions with no water flow), the average hourly energy consumption divided by the average hourly heat energy contained in stored water, expressed as a percent per hour. This can be converted to the average watts energy consumption required to maintain any water/air temperature difference by taking the percent times the temperature difference, times 1.15 kWh/($m^3 \cdot$ K) (a nominal specific heat for water), times the tank capacity, and then dividing by 100.

Standby loss coefficient. The heat input (in W/K) into a storage water heater when operated as specified in U.S. Department of Energy (DOE) test procedures (DOE 2001). This value is essentially the standby loss divided by the difference in temperature between the average stored water temperature and the surrounding air temperature. Care should be taken to understand whether a quoted standby loss coefficient includes the heat input efficiency of the heating device. It is possible to directly measure the heat lost from a storage water heater independently of how that water is heated. Sometimes, the reported standby loss coefficient represents only the heat lost; at other times, it represents the amount of energy to make up that heat loss, and considers the heat input efficiency of the heating device.

System standby loss. The amount of heat lost from the water heating system and the auxiliary power consumed during periods of nonuse of service hot water.

Thermal efficiency. Heat in water flowing from the heater outlet divided by the energy input to the heating unit over a specific period of steady-state conditions (includes heat losses from the water heater jacket and/or tank).

Uniform energy factor (UEF). The delivered efficiency of a residential or residential-duty commercial water heater when operated as specified in U.S. Department of Energy (DOE) test procedures (DOE 2014, 2016). This testing and rating procedure varies substantially from the earlier energy factor rating. The UEF test involves using one of four different hot water draw patterns, depending on capability of the water heater being tested.

Near-inlet-end heating (Figure 1). Heating water in the system near the cold-water inlet to the system storage tank(s) as opposed to near the hot water outlet of those tanks. Near-inlet-end heating systems usually have relatively simple controls.

Bottom-up heating (Figure 1). This is a form of near-inlet-end heating, where heat is input near the bottom of a storage tank. Bottom-up heating relies on thermal stratification between hotter water in the top of the storage tank (or in down-stream series connected tanks if more than one storage tank is present) and cooler water below which is being reheated. All the water below the thermocline (region where hotter and cooler water meet) will become the same temperature as storage is reheated, meaning that once the hotter water at the top of the storage tank (or in the outlet-end in series connected tanks) is depleted, more hot water cannot be delivered until the remainder of storage is all reheated.

Multi-pass heating. Water heating systems in which water in storage is reheated by either natural convection (buoyancy driven) or forced convection (pumped) recirculation, where each pass through the heating zone heats the water a relatively small amount compared to the ultimately desired outlet temperature delivered to users. This can be done with relatively simple controls.

Near-outlet-end heating (Figure 2). Heating water in the system close to the hot water outlet of the water heater. With this heating approach, heating priority in normally given to heat inputs or storage tanks that are closer to the hot outlet end of the system, making at least some amount of hot water quickly available for use.

Top-down heating (Figure 2). A form of near-outlet-end heating where priority is given to heating water in the system close to the hot-water outlet of the water heater over heating water closer to the cold-water inlet. To do this, more controls are needed than with near-inlet-end heating systems.

Single-pass heating (Figure 3). A form of near-outlet-end heating where water is heated from cold to hot-enough-to-use in a single pass through the heater such that the hot water produced can go directly to serve hot-water loads, with excess being provided to the outlet end of storage. (Introducing hot-enough-to-use water into the entering cold water in storage would waste the usefulness of that hot water.) Some form of water flow rate and/or heating rate modulation is necessary with this type of system. With properly sized single-pass heating systems, even if storage provided with that system becomes depleted, the system can continue to provide hot water without the need to reheat storage until later.

Instantaneous water heater. This term refers to any water heater, regardless of type (e.g., energy source, energy input rate, activation means, internal water/storage volume) that can reheat its stored volume fairly quickly. The most commonly used definition is any water heater having more than 300 W/L of water contained in the water heater, meaning a water heater that can reheat its stored volume faster than approximately 4 K/min. "Instantaneous" is not a type of water heater but rather a characteristic of a water heater.

Storage water heater. This is any water heater that contains some amount of stored water that is larger than the minimum amount needed to fill the region in the immediate vicinity where water heating occurs, and that maintains the stored water at a temperature that is immediately usable.

Tankless water heater. A water heater that contains only enough water to fill the unit's heating chambers (the region in the immediate vicinity of where energy is input to the water). Typical water volume contained in tankless water heaters varies from around 0.4 L for small point-of-use tankless water heaters to 8 to 19 L or more for fairly large commercial tankless heaters. Tankless water heaters can usually be characterized as instantaneous water heaters, but not all water heaters characterized as instantaneous are tankless. The terms "instantaneous" and "tankless" are not interchangeable, rather "tankless" water heaters are one type of "instantaneous" water heater. Normally tankless water heaters do not store hot water, but rather only heat water when draws are being taken.

3. SYSTEM PLANNING

The goals of system planning are to (1) size the system properly; (2) optimize system efficiency; (3) minimize first, operating, and overall life-cycle costs, and (4) ensure water heating systems are designed to operate safely and not adversely impact health and safety or water quality. It is important to design systems so that they perform well from both functional (hot-water delivery) and energy-use perspectives. Flow rate, temperature, and total flow over specific time periods are the primary factors to be determined in the design of a water-heating and piping system for delivering adequate amounts of hot water. Operating pressures, time of delivery, and water quality are also factors to consider. Presently, separate procedures are used to select water-heating equipment and to design the piping system. However, water-heating equipment sizing and piping system design should be considered together for best system design. Oversized or excessively long piping exacerbates delivery delay and/or energy waste, and causes slower water flow rates that may exacerbate pathogen growth in the water system.

Water-heating equipment, storage facilities, and piping should (1) have enough capacity to provide the required hot water while minimizing waste of energy or water and (2) allow economical system installation, maintenance, and operation.

Water-heating equipment types and designs are based on the (1) energy source, (2) heat exchange method, and (3) control method used to deliver the necessary hot water at the required temperature under varying water demand conditions. Application of water-heating equipment within the overall design of the hot-water system is based on (1) location of the equipment within the system, (2) related temperature requirements, (3) volume of water to be used, and (4) flow rate. Consideration of electricity demand charges on the utility bill is also of growing importance. Additional planning is required when the system providing the potable hot water is also used for space heating or other purposes. Some special water heater designs, made for this purpose, are known as combination space- and water-heating systems.

Energy Sources

Choice of energy source(s) is influenced by local availability of the various energy sources, equipment type, space considerations, locations of water heaters in structures, initial cost, operating cost, maintenance requirements, environmental impacts, and other factors. A life-cycle cost analysis is highly recommended.

In making energy conservation choices, consult ASHRAE *Standards* 90.1 and 90.2, or the sections on Service Water Heating Systems of ASHRAE *Standard* 100, as well as the section on Design Considerations in this chapter.

4. DESIGN CONSIDERATIONS

Hot-water system design should consider the following:

- Water heaters of different sizes and insulation may have different standby losses, thermal efficiency, or overall energy use.
- A distribution system should be properly laid out, sized, and insulated to deliver adequate water quantities at temperatures satisfactory for the uses served. This reduces standby loss and improves distribution system efficiency.

Locating fixtures or usage devices close to each other and to the water-heating equipment is particularly important for minimizing piping lengths and diameters, and thus reducing wait times as well as water and energy waste.

- Heat traps between recirculation mains and infrequently used branch lines reduce convection losses to these lines and improve distribution system efficiency. In small residential systems, heat traps can be applied directly to the water heater for the same purpose.
- Controlling circulating pumps to operate only as needed to maintain proper temperature at the end of the main reduces losses on return lines.
- Provision for shutdown of circulators during building vacancy reduces standby losses.
- Redundancy. For most large water heating systems, providing some amount of redundant water heating capacity is a good idea, such that water heating loads can still be met when some water heaters in the system are not operational or require maintenance. When water heaters are installed in flow parallel, using the same size heating rate and other design characteristics and the same set-point temperatures helps simplify flow and energy (run time) balancing. Moreover, when heaters are separate from storage tanks, multiple heaters can be installed in flow parallel with each other, but serving a single storage tank. Alternatively, they can each serve a separate (equal-sized) storage tank, with each of the storage tanks in flow parallel (non-operational tanks should be valved out of service). The amount of redundancy needed varies with criticality of the hot water loads to be served. For example, where life safety or loss of critical functions or data are possible, higher levels of backup and redundancy may be justified, compared to where the consequence is less critical, such as no warm water to wash hands for short periods. One technique for providing redundant backup heating is to provide an extra water heater having a heating capacity equal to the other water heaters in the system, allowing peak loads to be met when any one water heater and/or storage tank is out of commission. If design peak needed heating rate is Q, then for N equal-sized water heaters, each water heater needs to have a design heating rate of $Q/(N - 1)$, resulting in having an additional back-up heating capacity amounting to $1/(N - 1)$ of the total design load. For example, for $N = 5$, each water heater needs to have a design heating capacity of 1/4 of the design total needed heating rate. Four water heaters are needed to serve the design load, and the fifth provides a back-up capacity of another 1/4 of the design total needed heating rate. Workable combinations of total design needed heating rate and storage volume are determined the same way as for all systems.

Design Path for Savings

Reducing hot-water consumption not only results in lower water and sewer costs, it is the most effective way to reduce water-heating energy use. Designing in a reverse direction, starting with the hot-water-using equipment and moving back to the water heater and even further back to water treatment equipment whose size can also be impacted by magnitude of the hot-water loads (volume of hot water consumed), is an effective thought process to achieve higher system efficiency and performance.

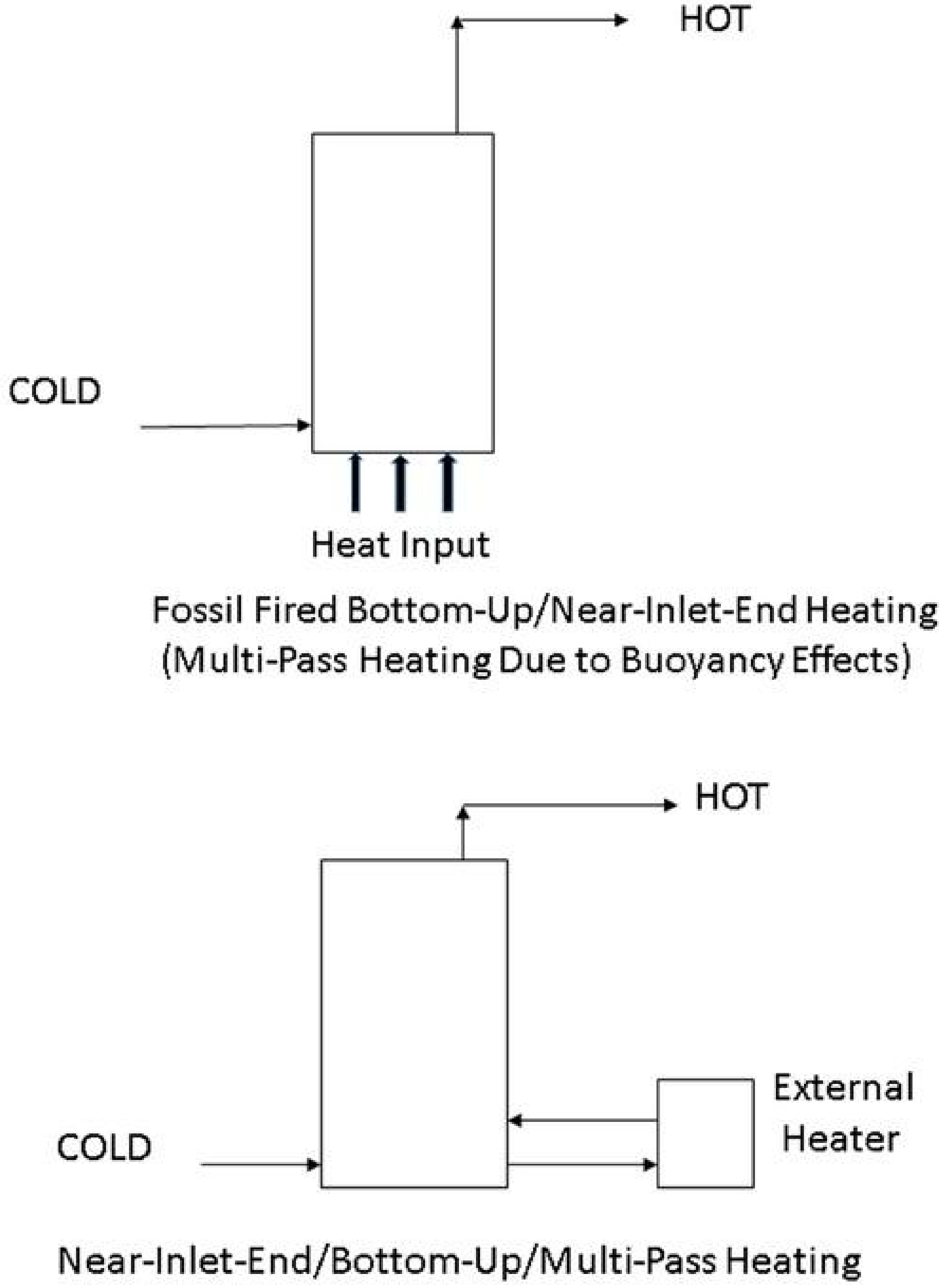

Figure 1. Near-Inlet-End/Bottom-Up/Multi-Pass Heating

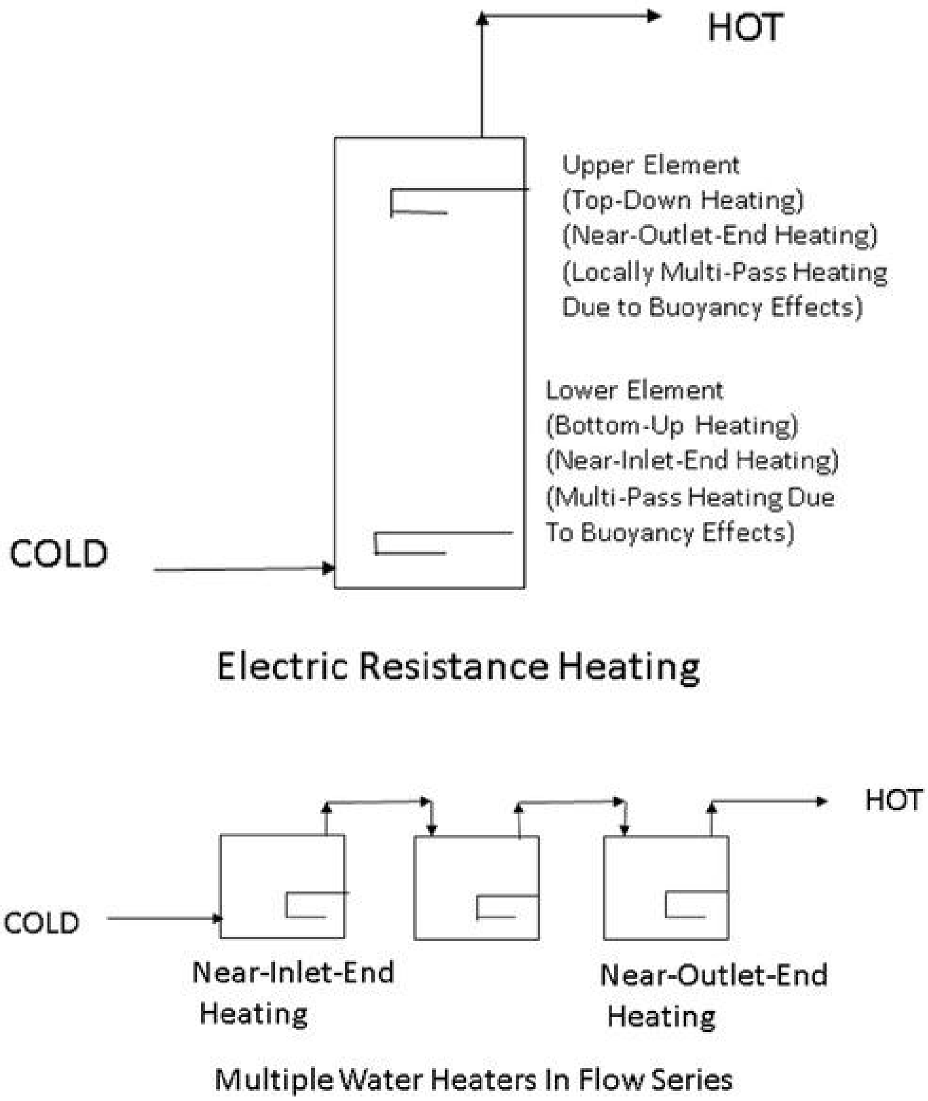

Figure 2. Near-Inlet-End/Bottom-Up versus Near-Outlet-End/Top-Down Heating

Step 1: Specify high-performance equipment and accessories that use less hot water, or alternative processes that eliminate the need for hot water for that particular task.

Step 2: Locate sinks and equipment in proximity to each other and to the water heater, and optimize the plumbing layout; these are key factors to the efficiency and performance of the overall system. Delivering hot water more efficiently yields permanent energy savings and improved hot-water delivery performance. Consider distributed generation or point-of-use heating for distant sinks where it does not make sense to extend the primary system's distribution system.

Step 3: Specify high-efficiency water heaters that are compatible with the distribution system and end-use fixtures. This is imperative.

Step 4: Before the hot-water system design is finalized, consider integrating preheating technologies such as heat recovery or solar heating.

Step 5: Verify proper installation of the system, including simple monitoring equipment, which can play an important role in commissioning and maintaining the system.

Step 6: When long hot-water piping systems are used, it may be necessary or advisable from a user satisfaction viewpoint to install hot-water recirculation loop pumps and piping so that piping can be kept hot to minimize hot-water delivery times. Keeping piping hot can also help inhibit pathogen growth. However, hot-water recirculation loops normally cause significant increases in system energy use because of prolonged heat loss from piping that is kept hot, so care should be taken to minimize the size and length of hot-water recirculation loop piping. Use of recirculation loops can easily more than double total water heating energy use. Using multiple separate water heating systems in buildings (even single-family residential) is one way to reduce or eliminate the need for hot water recirculation loops.

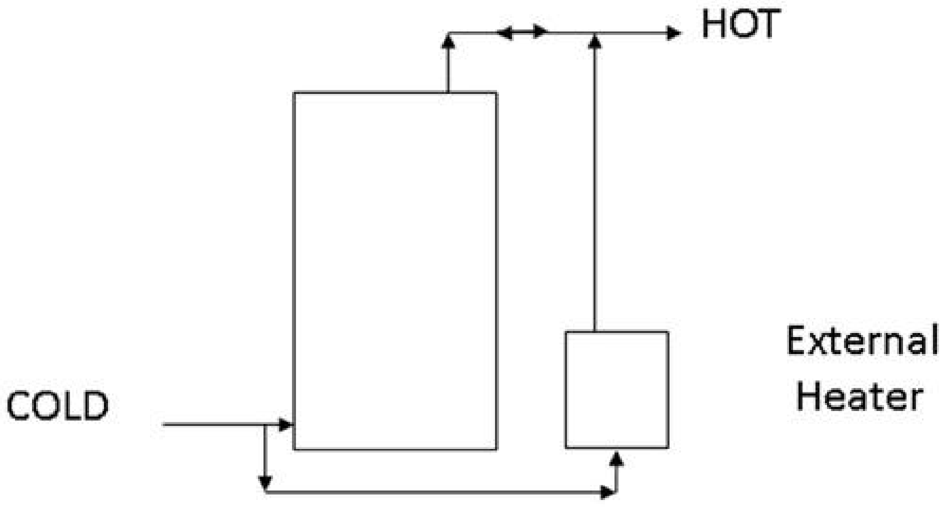

Figure 3. Single-Pass Heating

5. END-USE FIXTURES

Advanced end-use plumbing fixtures and appliances play an important role in reducing the size of the primary water heater(s) and simplifying the distribution system design. Use of high-efficiency, low-water-use equipment and fixtures, such as faucet aerators, reduced-flow (but still adequate) showerheads, and advanced clothes washers and dishwashers, provides multiple benefits, including the ability to use lower water temperatures and lowered total hot water consumption. Thus, in many instances, it is practical to provide localized heating devices, either near or built into the fixture or device, thereby additionally reducing distribution system heat losses and piping first costs. Providing localized heating devices also reduces demands on piping diameter and length for the remaining hot-water distribution system, and may reduce or eliminate the need for hot-water recirculation loops in some applications. The use of more water- and energy-efficient end-use fixtures and appliances is highly beneficial for improving efficiency, reducing energy use, and reducing environmental impacts.

The U.S. Energy Policy Act of 1992 established a maximum flow rate requirement for hand sink faucets and showerheads. These maximum flow rates were later revised and lowered to 30 mL/s for public hand sinks and 140 mL/sor private hand sinks. Faucet aerators that flow as low as 20 mL/sre now available. Similarly, manufacturers are now producing showerheads that use less than 113 mL/s, reduced from the federally mandated 160 mL/sflow rate. It is worthwhile noting that not all shower heads and other fixtures and appliances perform equally well, despite possibly having similar flow ratings and other hot-water use characteristics, so care in selection is advised. Specifying pressure-compensating flow regulation as opposed to fixed orifices for faucets and shower heads provides more constant flow rates over a wide range of operating pressures. Where possible, use of shorter, smaller-diameter piping, both hot and cold, can reduce hot-water delivery delays, reduce heat loss from piping, and improve flushing of piping, which improves disinfectant distribution.

Similar improvements have been made in fixtures and equipment for food-service industry hot-water systems. The U.S. Energy Policy Act of 2005 set a maximum flow rate of a prerinse spray valve at 100 mL/s (DOE 2011), reduced from conventional models rated at 160 to 285 mL/s. Spray valves flowing at 40 to 80 mL/s are now available. Dishwashers are now available with built-in heat recovery capability, which reduces dishwasher total energy and hot-water requirements and, when combined with localized or built-in heating ability, can significantly reduce hot-water demands on a building’s central hot-water system. Use of localized booster water heaters to produce the high water temperatures required for sanitization of wares in commercial dishwashers is commonplace and reduces temperatures required from a central hot-water system.

6. DISTRIBUTION

Piping Material

Traditional piping materials include galvanized steel used with galvanized malleable iron screwed fittings. Copper piping and copper water tube types K, L, or M have been used with brass, bronze, or wrought copper water solder fittings. PEX and CPVC piping materials are now used as an alternative in residential applications. Another alternative piping material is stainless steel tube. Particular care must be taken to ensure that the application meets the design limitations set by the manufacturer, particularly regarding temperature and pressure limits, and that the correct materials and methods of joining are used. These precautions are easily taken with new projects, but become more difficult during repairs of existing work. Using incompatible piping, fittings, and joining methods or materials must be avoided, because they can cause severe problems, such as corrosion or leakage caused by differential thermal expansion.

Today, most potable water supplies require treatment before distribution, which can cause the water to become more corrosive. Therefore, depending on the water supply, traditional galvanized steel piping or copper tube may no longer be satisfactory, because of accelerated corrosion. Galvanized steel piping is particularly susceptible to corrosion (1) when hot water is between 60 and 80°C and (2) where repairs have been made using copper tube without a nonmetallic coupling. Note that plumbing can be either piping (relatively thick wall) or tubing (relatively thin wall), although *piping* is used in this chapter for both. Before selecting any water piping material or system, consult the local code authority. The local water supply authority should also be consulted about any history of water aggressiveness causing failures of any particular material.

The Reduction of Lead in Drinking Water Act (effective January 4, 2014) prohibits the use of any pipe, pipe or plumbing fitting or fixture, and associated solder and flux used in all facilities for potable water piping that is not "lead free" as defined in section 1417(d) of the Safe Drinking Water Act, because of possible lead contamination of the water supply (EPA 2013).

Pipe Sizing

Sizing hot-water supply pipes from a hydraulic (pressure drop) perspective involves the same principles as sizing cold-water supply pipes (see Chapter 22 of the 2021 *ASHRAE Handbook—Fundamentals*). There may also be national or local code requirements for pipe sizing for certain applications.The water distribution system must be correctly sized for the total hot-water system to function properly. Hot-water demand varies with the type of establishment, usage, occupancy, and time of day. The piping system should be able to meet peak demand at an acceptable pressure loss. It is important not to oversize hot-water supply pipes, because this adversely affects system heat loss and overall energy use and can increase hot-water delivery delay times. Additionally, the lower flow velocities that result from oversized piping can increase piping heat loss by lowering temperature of the water, and allow sediment to collect that can exacerbate biological growth.

Supply Piping

Table 19, Figures 36 and 37, and manufacturers' specifications for fixtures and appliances can be used to determine hot-water demands. These demands, together with procedures given in Chapter 22 of the 2021 *ASHRAE Handbook—Fundamentals*, are used to size the mains, branches, and risers.

Allowance for pressure drop through the heater should not be overlooked when sizing hot-water distribution systems, particularly where instantaneous water heaters are used and where the available pressure is low.

Pressure Differential

Cold- and hot-water piping systems should be sized to minimize pressure differential at the point of use of blended hot and cold water. This is particularly important for tubs and showers, because sudden changes in flow at fixtures cause discomfort and a possible scalding hazard. Pressure-compensating anti-scald valves can minimize scald hazard, but remember to account for pressure loss through these devices in piping design.

Effect of Distribution Design on Efficiency of Condensing Heaters

Distribution system design and operation can have a significant impact on the efficiency of gas-fired condensing water heaters and other water heaters whose performance and efficiency vary significantly with temperatures (e.g., heat pump water heaters). Laboratory tests have shown a significant reduction in the ability of high-efficiency gas water heaters to maintain full condensing function because of elevated inlet-water temperatures. Figure 4 shows the reduction in thermal efficiency of a condensing tankless heater when inlet water temperatures are increased to simulate preheating equipment such as solar water heating systems and heat recovery devices (Huestis 2013; Johnson et al. 2013). The unit loses all condensing function at inlet temperatures of 54°C, where the thermal efficiency reaches 82%, typical of a standard-efficiency unit.

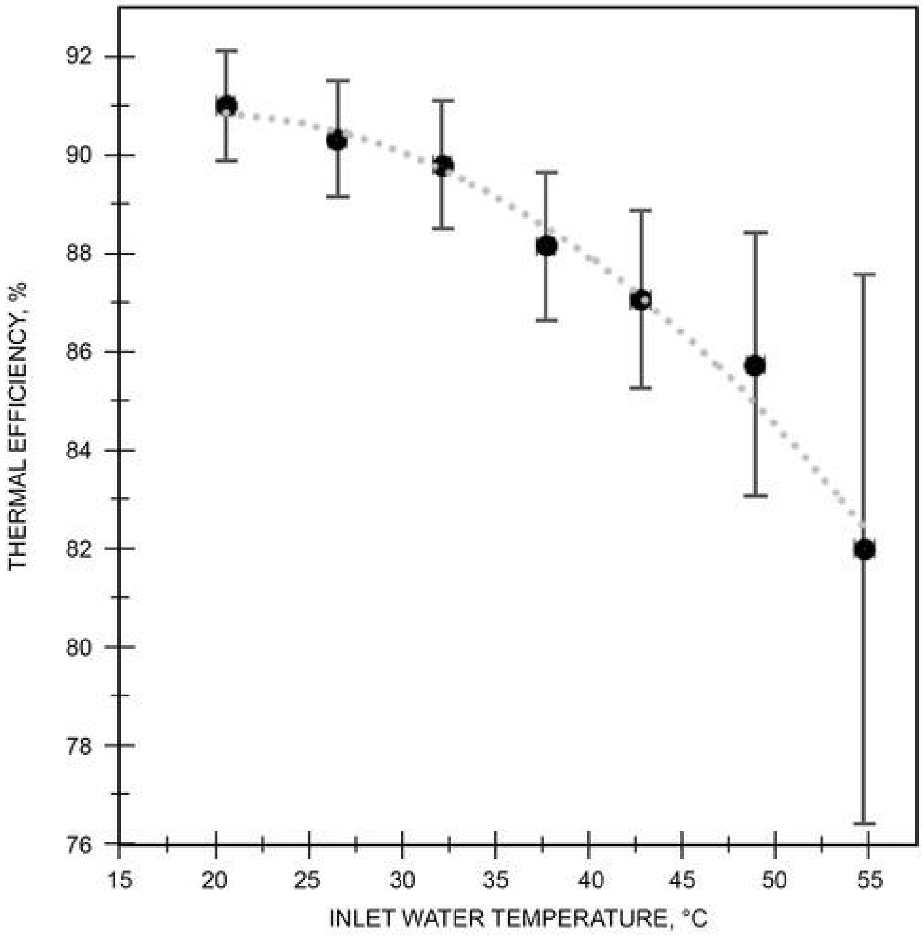

Figure 4. Effect of Inlet Water Temperature on Thermal Efficiency of Condensing Tankless Heater

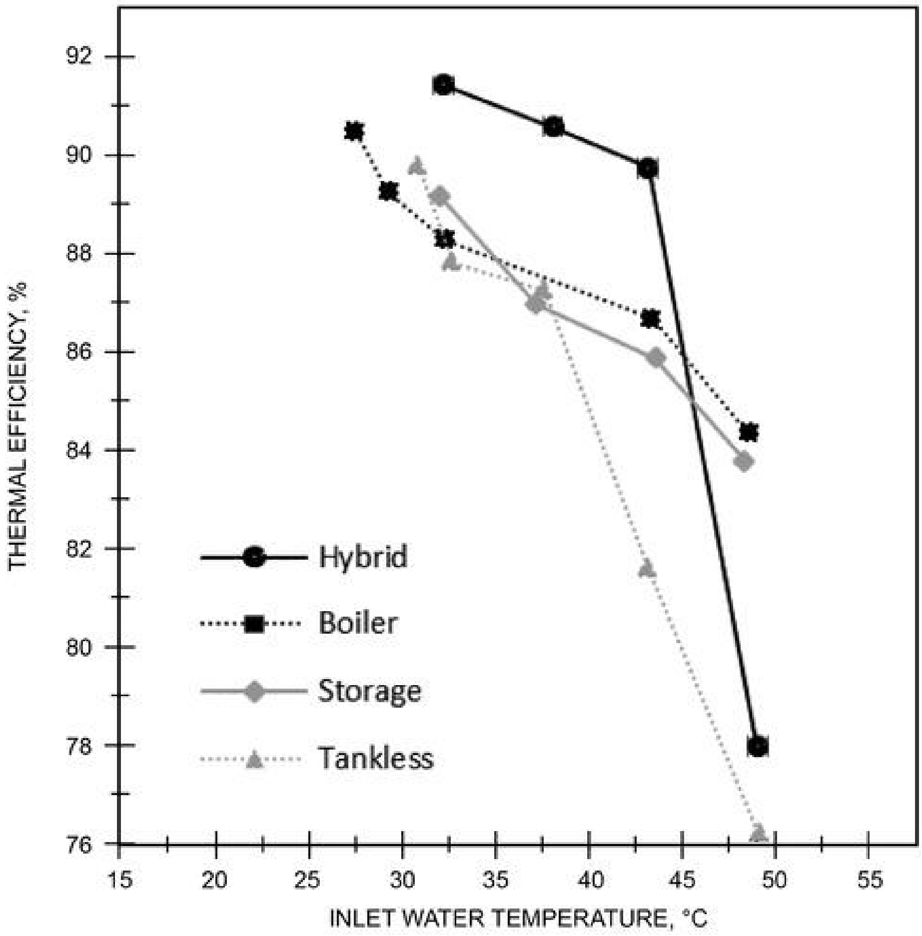

Figure 5. Effect of Return Water Temperature on Operating Efficiency of Condensing Heaters

A second study looked at the effect of continuous recirculation at a narrower band of return water temperatures on the operating efficiency of various heaters (Figure 5) with an outlet temperature of 54°C at 190 mL/s water flow rate (Schoenbauer 2012, 2013). This study shows consistent loss of thermal efficiency with higher return water temperatures observed at varying levels across product categories, though the specific loss of efficiency depends on unit design, specifically heat exchanger surface area and storage volume. The storage heater with a storage volume of 208 L and boiler with a flooded volume of less than 14 L demonstrated a steady decline in efficiency from approximately 90% thermal efficiency at 32°C to 84% efficiency at 49°C (partially condensing). For the hybrid heater with a storage volume of 7.6 L, the unit maintained condensing function with an average efficiency of 90% with a return water temperature from 32 to 43°C, but then the efficiency rapidly dropped to 78% at 49°C return water temperature. The tankless heater performed the worst, with a large drop in operating efficiency from 90% at 31°C to 76% efficiency at 49°C. Both the hybrid and tankless units lost the ability to capture latent heat from the exhaust gases at 49°C. There are alternatives to using continuous recirculation systems, including configuring system piping and recirculation system returns such that the recirculation loop water is introduced back to the water-heating system at a location that is closer to the hot-water outlet (but still upstream of at least one heating device so loop temperature can be maintained), which avoids mixing hot loop return water with entering cold water. This provides full entering cold-water temperatures to condensing water heaters or heat pump water heaters which will significantly improve their efficiency (see Figure 38 for one example of how to achieve that).

Table 1 Piping Heat Loss Factors for Foam Insulation with Thermal Conductivity of 0.114 W/(m^2 · K)

Nominal Pipe Size	Foam Insulation Thickness, mm	$UA_{zero\ flow}$, W/(m · K)	High-Value $UA_{flowing}$, W/(m · K)
13 mm rigid copper	0	0.391	0.623
	13	0.222	0.346
	19	0.201	0.329
19 mm rigid copper	0	0.672	0.762
	13	0.260	0.433
	19	0.246	0.415
19 mm rolled copper	0	0.579	0.579
	19	0.239	0.277
19 mm roll CU-sand	0	2.08	4.89
	19	0.269	0.307
19 mm PEX-AL-PEX[a]	0	0.952	0.945
	13	0.344	0.344
	19	0.273	0.312
19 mm PEX[b]	0	0.927	1.01
	19	0.276	0329
13 mm PEX	0	0.759	0.759
	19	0.225	0.225
10 mm PEX	0		
19 mm CPVC	0	0.762	0.901
	19	0.257	0.295

Note: Results are for horizontal in-air tests unless otherwise noted.
Sources: Hiller (2005a, 2005b, 2006b, 2008, 2009).
[a] High-density cross-linked polyethylene, aluminum, high-density cross-linked polyethylene multilayer pipe.
[b] High-density cross-linked polyethylene.

Piping Heat Loss and Hot-Water Delivery Delays

Good hot-water distribution system layout is very important, for both user satisfaction and energy use. This has become increasingly important with the mandated use of low-flow fixtures, which can cause lengthy delays and increased water waste while waiting for hot water to arrive at fixtures compared to higher-flow designs. In general, it is desirable to put fixtures close to each other and close to the water heater(s) that serve them. This minimizes both the diameter and length of the hot-water piping required. Recent work has shown that energy loss from hot-water piping due to both heat loss and water waste waiting for hot water to arrive at fixtures can be a significant percentage of total water-heating system energy use (Hiller 2005a; Klein 2004a, 2004b, 2004c; Lutz 2005). Energy losses from hot-water distribution systems usually amount to at least 10 to 20% of total hot-water system energy use in most potable water-heating systems (Hiller 2005a), and are often as high as 50%; losses of over 90% have been found in some installations (Hiller and Miller 2002; Hiller et al. 2002).

Hiller (2005a, 2005b, 2006a, 2006b) measured both piping heat loss and time, water, and energy waste while waiting for hot water to arrive at fixtures. This research measured piping heat loss *UA* factors for several commonly used piping sizes, types, and insulation levels. See ASHRAE *Standard* 90.1 for pipe insulation requirements. $UA_{flowing}$ values are a slight function of water flow rate and temperature difference between the hot water and the surroundings. However, for many practical calculation purposes, *UA* can be considered constant at the values shown in Table 1.

Hiller (2008) found that bare copper piping buried in damp sand (typical of under-slab piping) exhibited heat loss rates over eight times higher than the same pipe in air. This much higher heat loss rate is believed to be caused by moisture in the sand near the pipe behaving like a heat pipe by evaporating, recondensing (thus transferring heat to sand particles a short distance away much faster than conduction would), and then wicking back to the pipe. Adding insulation to buried piping dramatically reduced the heat-pipe effect by lowering the surface temperature seen by the moisture. Hence, as can be seen in Table 1, adding 19 mm foam pipe insulation to copper piping reduces the heat loss rate in air to around one-half of the uninsulated value, but adding the same insulation to pipe buried in damp sand reduces the heat loss rate to only around 6% of its uninsulated value, a reduction by a factor of around 16. Thus adding pipe insulation is highly beneficial for buried piping, and is recommended.

Table 1 also shows that all of the plastic pipes tested to date exhibit moderately to significantly higher heat loss rates than comparably sized copper pipes when tested uninsulated in air. However, when insulated, they exhibit moderately to significantly lower heat loss rates than comparably sized copper pipes with the same insulation. Adding 19 mm foam reduces plastic pipe heat loss rates to around 30% of their uninsulated values when tested in air. This is a reduction in heat loss rate by a factor of three, compared to a factor of two for insulation on copper piping. This result suggests that plastic pipes have higher emissivity for radiation heat loss from the piping than does copper. Theoretical analysis suggests that, for the pipe sizes tested, radiation heat loss from the pipes represents between 30% and 70% of total heat loss rate from the pipes, depending on pipe type and size. It has been suggested that the emissivity of copper pipe may increase with age as the outer surface oxidizes to its normal dull-brown appearance from its original bright, shiny surface. Repeat tests on aged copper pipe have not yet been performed.

The *UA* factors of Table 1 are used in Equations (1) to (8) to determine heat loss rates from piping during both flowing and zero-flow (cooldown) conditions, and to find temperature drop while water is flowing through pipe, and pipe temperature at any time during cooldown. Note that piping heat loss and pipe temperature drop are not constant with length under flowing conditions, because the temperature of each successive length of pipe is less than the one before it. The same is true for zero-flow pipe cooldown with respect to time, because the pipe is at a progressively lower temperature at each successive time interval. The result is that pipe temperatures decay inverse-exponentially with length under flowing conditions and with time under cooldown conditions. This is why log-mean temperature difference must be used in heat loss calculations instead of a simple linear temperature difference (Rohsenow and Choi 1961).

Table 2 Approximate Heat Loss from Piping at 60°C Inlet, 21°C Ambient

Nominal Size, mm	Bare Copper Tubing, W/m	Bare Copper *UA*, W/(m·K)	13 mm Glass Fiber Insulated Copper Tubing, W/m	13 mm Glass Fiber Insulated Copper *UA*, W/(m·K)
19	29	0.74	17.0	0.43
25	37	0.93	19.5	0.50
32	43	1.11	22.5	0.57
38	51	1.32	24.4	0.62
50	63	1.63	28.5	0.73
64	77	1.97	32.5	0.83
75	90	2.32	38.0	0.96
100	115	2.96	46.5	1.19

Under flowing conditions,

$$Q = mc_p(T_{hot\ in} - T_{hot\ out}) \quad (1)$$

and

$$Q = UA_{flowing} L_{pipe} \Delta T_{lm} \quad (2)$$

For water flowing in pipes in a constant-air-temperature environment,

$$\Delta T_{lm} = \frac{[(T_{hot\ in} - T_{air}) - (T_{hot\ out} - T_{air})]}{\ln[(T_{hot\ in} - T_{air})/(T_{hot\ out} - T_{air})]} \quad (3)$$

When $UA_{flowing}$, water flow rate, air temperature, and entering water temperature are known, Equations (1) to (3) can be combined and rearranged to determine pipe-exiting water temperature as follows:

$$T_{hot\ out} = T_{air} + (T_{hot\ in} - T_{air})e^{-\left[\frac{(UA_{flowing})(L_{pipe})}{(mc_{p_{water}})}\right]} \quad (4)$$

where

ΔT_{lm}	=	log mean temperature difference, K
Q	=	heat loss rate, W
m	=	water flow rate, kg/s; (density)(volumetric flow rate)

c_p	=	specific heat of water, 4186.8 J/(kg · K)
$T_{hot\ in}$	=	water temperature entering pipe, °C
$T_{hot\ out}$	=	water temperature leaving pipe, °C
$UA_{flowing}$	=	flowing heat loss factor per metre of pipe, W/(m · K)
L_{pipe}	=	length of hot-water pipe, m

Note that the quantity $(UA_{flowing})(L_{pipe})/(mc_p)_{water}$ must be nondimensional, so appropriate units must be used.

Under zero-flow cooldown conditions,

$$Q = (Mc_p)_{w,p,i}\ (T_{hot\ t_1} - T_{hot\ t_2})/(t_2 - t_1) \tag{5}$$

$$Q = UA_{zero\text{-}flow}(\Delta T_{lm}) \tag{6}$$

And for pipe in a constant-air-temperature environment:

$$\Delta T_{lm} = \frac{[(T_{hot\ t_1} - T_{air}) - (T_{hot\ t_2} - T_{air})]}{\ln[(T_{hot\ t_1} - T_{air})/(T_{hot\ t_2} - T_{air})]} \tag{7}$$

$$T_{hot\ t_2} = T_{air} + (T_{hot\ t_1} - T_{air})e^{-\left[\frac{(UA_{zero\text{-}flow})(t_2 - t_1)}{(Mc_p)_{w,p,i}}\right]} \tag{8}$$

where

t_1	=	initial time
t_2	=	final time
Q	=	average heat loss rate from time t_1 to time t_2, W/m
$(Mc_p)_{w,p,i}$	=	sum of mass times specific heat for water, pipe, and insulation, J/(m · K)
$T_{hot\ t_1}$	=	pipe temperature at t_1, °C
$T_{hot\ t_2}$	=	pipe temperature at t_2, °C
$UA_{zero\text{-}flow}$	=	zero-flow heat loss factor per metre of pipe, W/(m · K)

Note that the quantity $(UA_{zero\text{-}flow})(t_2 - t_1)/(Mc_p)_{w,p,i}$ must be nondimensional, so appropriate units must be used.

Pipe temperature at any time during the cooldown process is determined by Equation (8). Total energy lost from piping during zero-flow cooldown is determined by calculating the pipe temperature at time t_2 and multiplying the average heat loss rate between t_1 and t_2 determined by Equation (5) times the duration of the cooldown period $(t_2 - t_1)$. An alternative is to calculate heat loss over short time periods using Equation (6) and sum the results.

Table 2 contains earlier piping heat loss data, and shows computed piping *UA* values based on those data.

Hiller (2005a, 2005b, 2006b) also produced tables of water/energy wasted while waiting for hot water to arrive at fixtures. Waste is a strong function of pipe material, interior finish, diameter, fittings present, flow rate, initial pipe temperature, and entering hot-water temperature. The amount of water wasted to drain is generally an amount greater than pipe volume because temperature of some of the first hot water traveling through the pipe is degraded to below a usable temperature.

Initial flow of hot water into a pipe full of cooler water often does not behave as predicted by steady-state flow theory, because both hot and cold water are flowing simultaneously in the same pipe (a non-steady-state condition). At least three different flow regimes were identified: (1) stratified flow (at low flow rates in horizontal pipes, hot water flows farther along the top side of the pipe than on the bottom side; this can happen even in small-diameter pipes), (2) normal turbulent flow, and (3) shear flow (a relatively sharp hot/cold interface with little turbulence-induced mixing of hot and cold water because the normal boundary layer is slow to develop under some conditions). These flow regimes are important because each causes different amounts of temperature degradation as hot water flows through the pipe.

For detailed information on time, water, and energy waste while waiting for hot water to arrive at fixtures, see Hiller (2005b). Simply summarized here, the amount of water waste can be expressed as the ratio of the actual amount of water (actual flow or AF) wasted while waiting for hot-enough-to-use water to arrive at fixtures (defined as 40.5°C by Hiller) divided by pipe volume (PV). When the pipe cools below a usable temperature, AF/PV ratios are usually in the range of 1.0 to 2.0, but can go to infinity at low flow rates in long, uninsulated pipe in cold or otherwise adverse (e.g., damp) heat transfer environments. The critical length of pipe at which AF/PV goes to infinity can be calculated for any flow rate and temperature conditions, using the piping $UA_{flowing}$ factors and Equations (1) to (4).

For preliminary engineering design and energy use calculations, Hiller recommends assuming AF/PV values of 1.25 to 1.75. For more refined analyses, accounting better for temperature effects on AF/PV ratio, the data tables in the original reference should be consulted. More such data on a larger variety of pipe sizes, types, and environments would be beneficial, but are not currently available.

Examples 12 to 15 demonstrate how to use piping heat loss and delivery water waste information to calculate hot-water system energy use.

Hot-Water Recirculation Loops and Return Piping

Hot-water recirculation loops are commonly used where piping lengths are long and hot water is desired immediately at fixtures. In recirculation-loop systems, return piping and a circulation device are provided. Some recirculation-loop systems use buoyancy-driven natural convection forces to circulate flow, but most are equipped with circulating pumps to force water through the piping and back to the water heater, thus keeping water in the piping hot.

The water circulation pump may be controlled by a thermostat (in the return line) set to start and stop the pump over an acceptable temperature range. This thermostat can significantly reduce both heat loss and pumping energy in some applications. An automatic time switch or other control should turn water circulation off when hot water is not required. Other, more advanced circulating pump control schemes, such as on-demand types using manual initiation, flow switches, or occupancy sensors, are also available. Because hot water is corrosive, circulating pumps should be made of corrosion-resistant material. See ASHRAE *Guideline* 12-2020 for loop temperature recommendations.

For small installations, a simplified pump sizing method is to allow 60 mL/s for every fixture unit in the system, or to allow 30 mL/s for each 20 or 25 mm riser; 60 mL/s for each 32 or 40 mm riser; and 130 mL/s for each riser 50 mm or larger.

Dunn et al. (1959) and Werden and Spielvogel (1969a, 1969b) discuss heat loss calculations for large systems. For larger installations, piping heat losses become significant. A quick method to size the pump and return for larger systems is as follows:

1. Determine total length of all hot-water supply and return piping.
2. Choose an appropriate value for piping heat loss from Tables 1 or 2 or other engineering data (usually supplied by insulation companies, etc.). Multiply this value by the total length of piping involved.

   A rough estimation can be made by multiplying the total length of covered pipe by 30 W/m or uninsulated pipe by 60 W/m. Table 2 gives actual heat losses in pipes at a service water temperature of 60°C and ambient temperature of 21°C. The values of 30 or 60 W/m are only recommended for ease in calculation.
3. Determine pump capacity as follows:

$$Q = \frac{q}{\rho c_p \Delta t} \quad \textbf{(9)}$$

   where

Q_p	=	pump capacity, L/s
q	=	heat loss, W
ρ	=	density of water = 0.99 kg/L (50°C)
c_p	=	specific heat of water = 4186.8 J/(kg · °C)
Δt	=	allowable temperature drop, K

   For a 10 K allowable temperature drop,

$$Q_p(\mathrm{L/s}) = \frac{q}{0.99 \times 4186.8 \times 10} = \frac{q}{41\,450} \quad \textbf{(10)}$$

   Caution: This calculation assumes that a 10 °C temperature drop is acceptable at the last fixture.
4. Select a pump to provide the required flow rate, and obtain from the pump curves the pressure created at this flow.
5. Check that the pressure does not exceed the allowable friction loss per metre of pipe.
6. Determine the required flow in each circulating loop, and size the hot water return pipe based on this flow and the allowable friction loss from Step 5.

Where multiple risers or horizontal loops are used, balancing valves with means of testing are recommended in the return lines before where they join shared return pipes. A swing-type check valve should be placed in each such return to prevent entry of cold water or reversal of flow, particularly during periods of high hot-water demand.

Three common methods of arranging circulation lines are shown in Figure 6. Although the diagrams apply to multistory buildings, arrangements (A) and (B) are also used in residential designs. In circulation systems, air venting, pressure drops through the heaters and storage tanks, balancing, and line losses should be considered. In Figures 3A and 3B, air is vented by connecting the circulating line below the top fixture supply. With this arrangement, air is eliminated from the system each time the top fixture is opened. Generally, for small installations, a nominal pipe size (NPS) 15 or 20 mm hot-water return is ample.

All storage tanks and piping on recirculating systems should be insulated as recommended by the ASHRAE *Standard* 90 series and *Standard* 100.

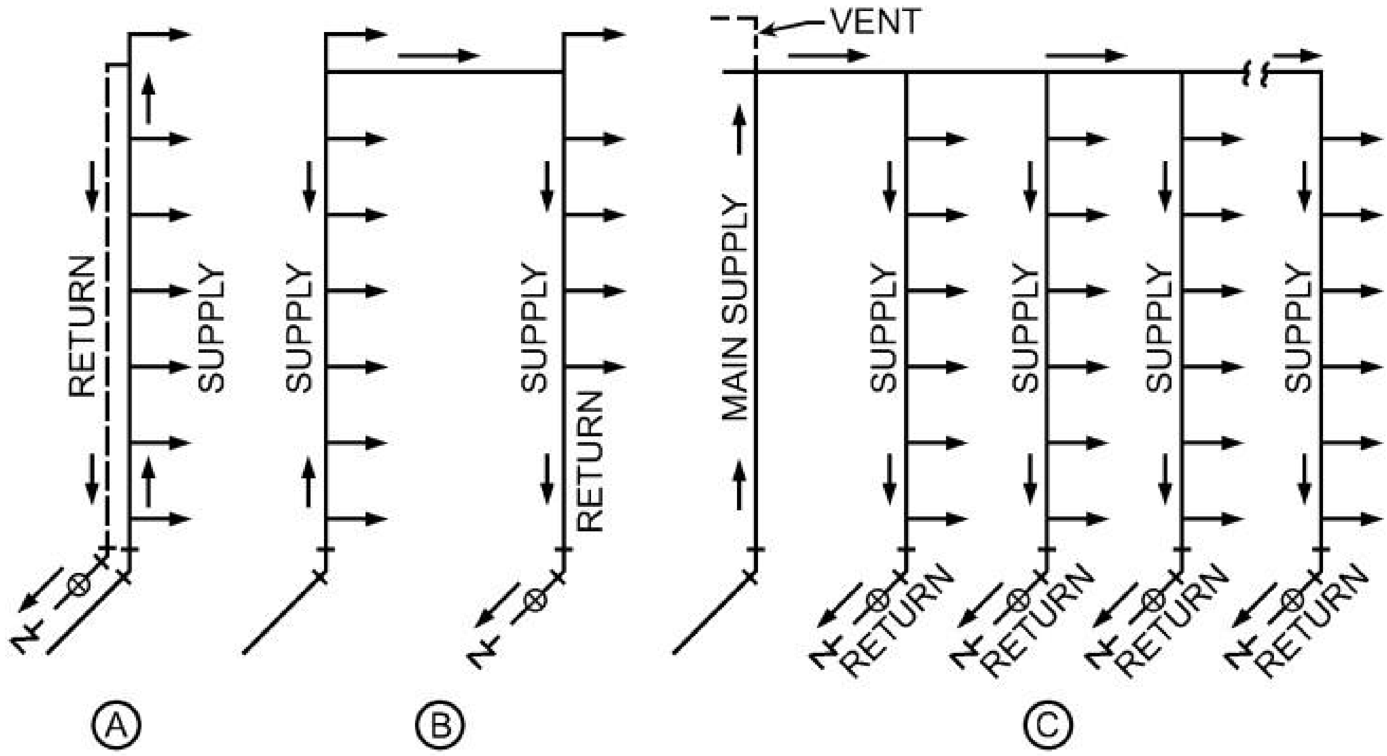

Figure 6. Arrangements of Hot-Water Circulation Lines

Heat-Traced, Nonreturn Piping

In this system, the fixtures can be as remote as in the hot-water recirculation loops and return piping section. The hot-water supply piping is heat traced with electric resistance heating cable preinstalled under the pipe insulation. Electrical energy input is self-regulated by the cable's construction to maintain the required water temperature at the fixtures. No return piping system or circulation pump is required.

Multiple Water Heaters

Depending on fixture spacing, required pipe lengths, and draw spacing, it may be more energy-efficient (and sometimes provide lower first cost) to use more than one water heater rather than using extensive piping runs. Energy losses from high-efficiency water heaters can be lower than recirculation-loop piping heat losses if the distance from water heaters to fixtures exceeds 10 to 20 m (Hiller 2005a). Although there are considerations beyond energy use, such as installation, maintenance, and space requirements, using more than one water heater should always be evaluated when designing water heating systems, even in residences, because of the potentially large energy savings.

Commercial Dishwasher Piping and Pressure Considerations

Adequate flow rate and rinse pressure must be maintained for automatic dishwashers to achieve efficient dishwashing in commercial kitchens. National Sanitation Foundation (NSF) standards for dishwasher water flow pressure are 100 kPa (gage) minimum, 170 kPa (gage) maximum, and 140 kPa (gage) ideal. Flow pressure is the line pressure measured when water is flowing through the rinse arms of the dishwasher.

Low flow pressure can be caused by undersized water piping, stoppage in piping, or excess pressure drop through heaters. Low water pressure causes an inadequate rinse, resulting in poor drying and sanitizing of the dishes. If flow pressure in the supply line to the dishwasher is below 100 kPa (gage), a booster pump or other means should be installed to provide supply water at 140 kPa (gage).

Flow pressure over 170 kPa (gage) causes atomization of the 82°C rinse water, resulting in excessive temperature drop (which can be as much as 8 K between rinse nozzle and dishes). A pressure regulator should be installed in the supply water line adjacent to the dishwasher and external to the return circulating loop (if used).

To reduce operating difficulties, piping for automatic dishwashers should be installed according to the following recommendations:

- The cold-water feed line to the water heater should be no smaller than NPS 25 mm.
- The supply line that carries 82°C water from the water heater to the dishwasher should not be smaller than NPS 19 mm.
- No auxiliary feed lines should connect to the 82°C supply line.

- A return line should be installed if the source of 82°C water is more than 1.5 m from the dishwasher.
- Forced circulation by a pump should be used if the water heater is installed on the same level as the dishwasher, if the length of return piping is more than 18 m, or if the water lines are trapped.
- If a circulating pump is used, it is generally installed in the return line. It may be controlled by (1) the dishwasher wash switch, (2) a manual switch located near the dishwasher, or (3) an immersion or strap-on thermostat located in the return line.
- A pressure-reducing valve should be installed in the low-temperature supply line to a booster water heater, but external to a recirculating loop. It should be adjusted, with the water flowing, to the value stated by the washer manufacturer.
- A check valve should be installed in the return circulating line.
- If a check-valve water meter or a backflow prevention device is installed in the cold-water line ahead of the heater, it is necessary to install a properly sized diaphragm-type expansion tank between the water meter or prevention device and the heater.
- NSF standards require an NPS 6 mm IPS connection for a pressure gage mounted adjacent to the supply side of the control valve. They also require a water-line strainer ahead of any electrically operated control valve (Figure 7).
- NSF standards do not allow copper water lines that are not under constant pressure, except for the line downstream of the solenoid valve on the rinse line to the cabinet.

Two-Temperature Service

Where multiple temperature requirements are met by a single system, the system temperature is determined by the maximum temperature needed. Where the bulk of the hot water is needed at the higher temperature, lower temperatures can be obtained by mixing hot and cold water. Automatic mixing valves reduce the temperature of the hot water available at certain outlets to prevent injury or damage (Figure 8). Applicable codes should be consulted for mixing valve requirements.

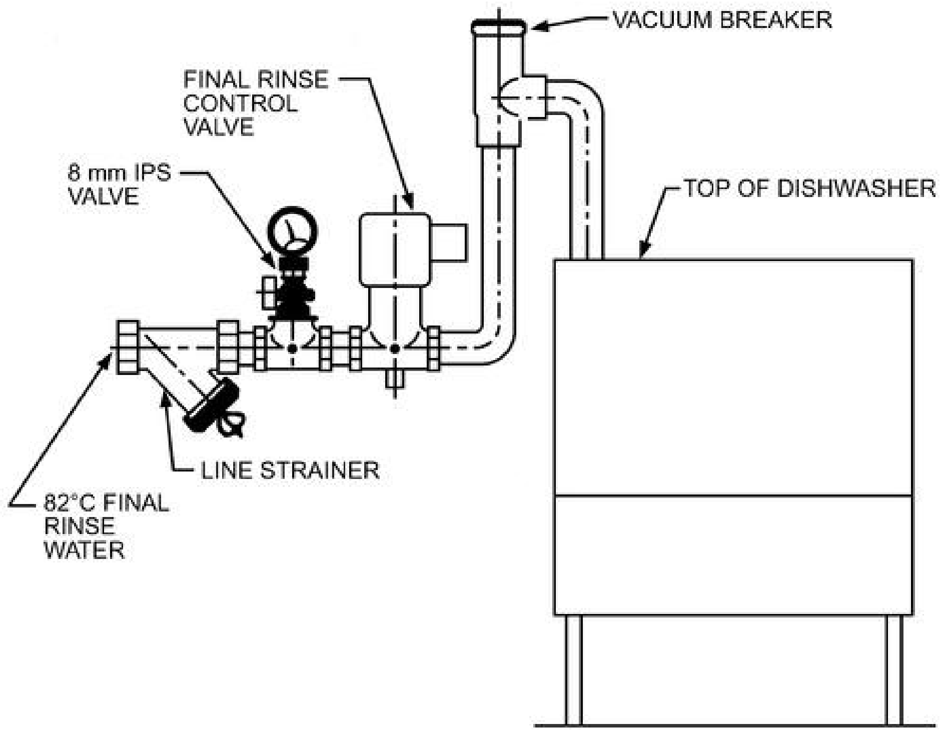

Figure 7. National Sanitation Foundation (NSF) Plumbing Requirements for Commercial Dishwasher

Where predominant use is at a lower temperature, the common design heats all water to the lower temperature and then uses a separate booster heater to further heat the water for the higher-temperature service (Figure 9). This method offers better protection against scalding.

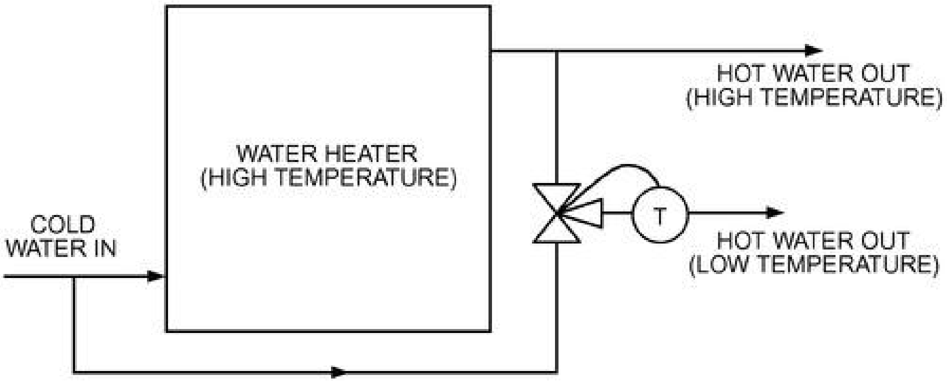

Figure 8. Two-Temperature Service with Mixing Valve

A third method uses separate heaters for the higher-temperature service ([Figure 10](#)). It is common practice to cross-connect the two heaters, so that one heater can serve the complete installation temporarily while the other is valved off for maintenance. Each heater should be sized for the total load unless hot-water consumption can be reduced during maintenance periods.

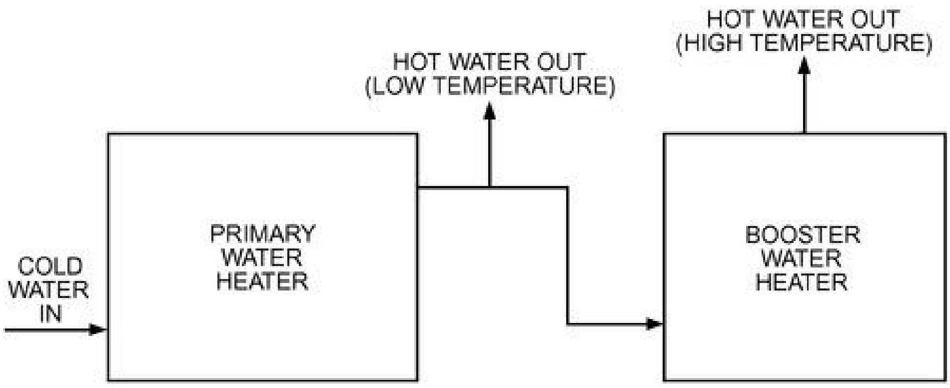

Figure 9. Two-Temperature Service with Primary Heater and Booster Heater in Series

Manifolding

Where one heater does not have sufficient capacity, two or more water heaters may be installed in parallel. If blending is needed, a single mixing valve of adequate capacity should be used. It is difficult to obtain even flow through parallel mixing valves.

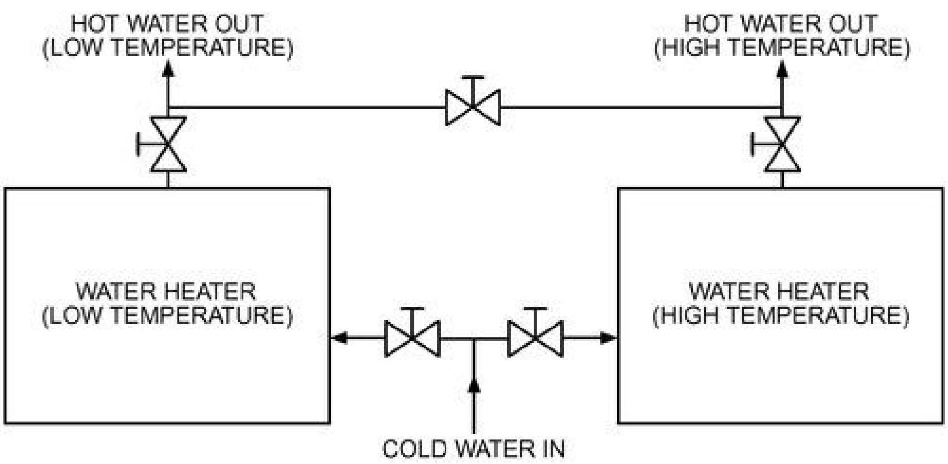

Figure 10. Two-Temperature Service with Separate Heater for Each Service

Heaters installed in parallel should have similar specifications: the same input and storage capacity, with inlet and outlet piping arranged so that an equal flow is received from each heater under all demand conditions.

An easy way to get balanced, parallel flow is to use reverse/return piping ([Figure 11](#)). The unit having its inlet closest to the cold-water supply is piped so that its outlet is farthest from the hot-water supply line. Quite often this results in a hot-water supply line that reverses direction (see dashed line, [Figure 11](#)) to bring it back to the first unit in line; hence the name reverse/return.

Care must be used in commissioning heaters in parallel flow. Field testing (Hiller and Johnson 2015) showed that having water heaters in parallel flow can result in each heater having dramatically different numbers of on/off firing cycles: an important consideration in equipment life and maintenance. Having heaters set to even slightly different on/off temperatures can cause the heater set to the highest temperatures to come on first and end up being the only heater to fire to make up most of the heat loss from the storage and distribution system.

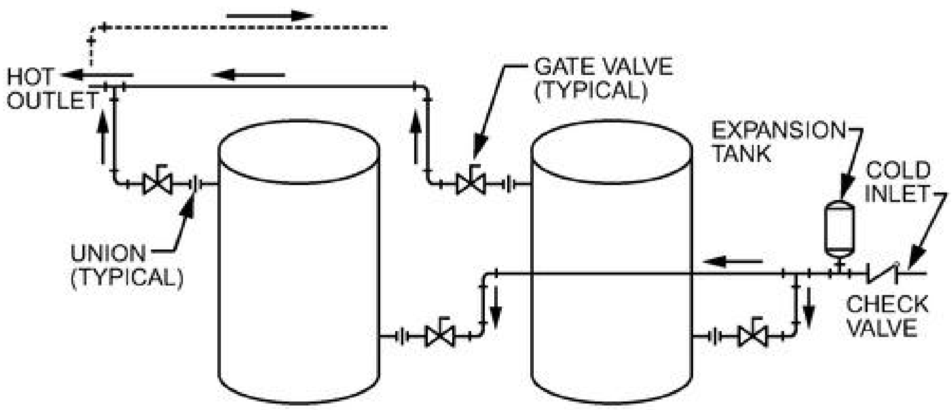

Figure 11. Reverse/Return Manifold System

7. WATER-HEATING EQUIPMENT

Gas-Fired Systems

See the section on Water-Heating Terminology for definitions of storage, tankless, instantaneous gas-fired, and other specific types of water heaters.

Tankless water heaters have almost no storage capacity, and do not keep water hot but rather heat water as it flows once through the water heater. Heating rate required varies with water flow rate and needed temperature rise. Most modern gas-fired tankless water heaters have a flow switch or equivalent to confirm flow before the burner activates. Some have advanced multistage or modulating burners to better control outlet temperature. Some also incorporate fixed or modulating water flow rate controls to ensure that water temperature reaches at least a minimum outlet temperature (i.e., it restricts flow rate, possibly below that which the user requested, to avoid undesirably cool outlet water temperature if burners are already operating at maximum heating rate). Most advanced designs also incorporate electronic ignition controls, thus minimizing standby energy losses compared to having a tank and continuously burning pilot light. Properly applied tankless water heaters thus have lower overall energy use and higher efficiency compared to minimum-efficiency tank types serving the same loads. Note, however, that tankless water heaters have on/off cycling-rate-related energy losses that, under water draw events of a small volume, short duration, or intermittent nature may reduce their system efficiency and hot water delivery performance (Glanville et al. 2013). They may also have minimum flow rate requirements before they activate, which may require users to modify their behavior (e.g., use a higher flow rate than they normally would and/or leave water running when they would normally turn it off) to obtain hot water. Sometimes, it may be beneficial to reduce the hot-water delivery temperature to reduce point-of-use mixing with cold water, thereby increasing hot-water flow rate.

Circulating tank water heaters are classified in two types: (1) automatic, in which the thermostat is located in the water heater, and (2) nonautomatic, in which the thermostat is located within an associated storage tank.

Hot-water supply boilers are capable of providing service hot water. They are typically installed with separate storage tanks and applied as an alternative to circulating tank water heaters. Outdoor models are wind- and rain-tested. They are available in most of the classifications previously listed.

Direct-vent models are installed indoors, but are not vented through a conventional chimney or gas vent and do not use ambient air for combustion. They must be installed with the means specified by the equipment manufacturer for venting (typically horizontal) and for supplying combustion air from outside the building.

Power vent equipment uses a powered fan or blower to move combustion products, allowing horizontal as well as vertical venting.

Direct-fired equipment passes cold water through a stainless steel or other heat exchange medium, which breaks up the water into very small droplets. These droplets then come into direct contact with heat rising from a flame, which heats the water directly.

Residential water-heating equipment is usually the automatic storage type, although increasing numbers of tankless water heaters are being installed. For industrial and commercial applications, commonly used types of heaters are (1) automatic storage, (2) circulating tank, (3) instantaneous, (4) tankless and (5) hot-water supply boilers.

Installation guidelines for gas-fired water heaters can be found in the National Fuel Gas Code, NFPA *Standard* 54/ANSI *Standard* Z223.1. This code also covers sizing and installation of venting equipment and controls.

Oil-Fired Systems

Oil-fired water heaters are generally the storage tank type. Models with a storage tank of 200 L or less with an input rating of 30 kW or less are usually considered residential models. Commercial models are offered in a wide range of input ratings and tank sizes. There are models available with combination gas/oil burners, which can be switched to burn either fuel, depending on local availability.

Installation guidelines for oil-fired water heaters can be found in NFPA *Standard* 31/ANSI *Standard* Z95.1.

Electric

The most common electric water heaters are generally the storage type, consisting of a tank with one or more immersion heating elements. The heating elements consist of resistance wire embedded in refractories having good heat conduction properties and electrical insulating values. Heating elements are fitted into a threaded or flanged mounting for insertion into a tank. Thermostats controlling heating elements may be of the immersion or surface-mounted type.

Residential storage tank water heaters range up to 450 L with input up to 12 kW. They have a primary resistance heating element near the bottom and often a secondary element located in the upper portion of the tank. Each element is controlled by its own thermostat. In dual-element heaters, the thermostats are usually interlocked so that the lower heating element cannot operate if the top element is operating. Thus, only one heating element operates at a time to limit current draw.

Commercial storage tank water heaters are available in many combinations of element quantity, wattage, voltage, and storage capacity. Storage tanks may be horizontal or vertical. Compact, low-volume models are used in point-of-use applications to reduce hot-water piping length. Locating the water heater near the point of use makes recirculation loops unnecessary.

Instantaneous or tankless electric water heaters have almost no storage capacity and heat water as it flows once through the water heater, so water is not kept hot but rather is only heated upon sensing flow. Heating rate required varies with water flow rate and needed temperature rise. Tankless electric water heaters for residential applications are available in heating capacities from a low of about 1.5 kW to a high of about 60 kW. Smaller-capacity units (typically 12 kW or less, but this varies with geographic location and entering cold-water temperature) are sometimes used in lavatory (sink) and other point-of-use applications such as remote low-use showers, small hot tubs, whirlpool baths, and other low-flow-rate applications. Larger sizes (above 18 kW) can sometimes be used in whole-house applications, depending on geographic location (and hence entering cold water temperature) and site hot-water use profiles (see Table 18). Tankless water heaters can, if equipped with appropriate controls, be used in booster and/or recirculating water-heating systems. Note that not all models can be used to heat already partially warmed water: this capability varies among models. Tankless water heaters are one type of instantaneous water heater.

Heat pump water heaters (HPWHs) use a vapor-compression or sorption refrigeration cycle to extract energy from an air, ground, or water source to heat water. HPWHs may be designed as a single package with the refrigeration system and storage water tank as an integral system; or as the refrigeration system alone, sometimes referred to as an "add-on" or "without tank" heat pump water heater, which is connected to a separately specified storage water tank, the size of which is generally dependent upon the application requirements. HPWHs can generate hot-water temperatures up to 60°C, with some models capable of outlet temperatures in the 82°C range. Where a higher delivery temperature is required than the HPWH can produce, a supplemental or booster water heater downstream of the storage tank should be used. HPWHs function most efficiently where inlet water temperature is low and the heat source temperature is warm. HPWHs frequently benefit from greater storage tank capacity than standard water heaters for the application because that enables the use of smaller HPWHs with lower first cost. The use of greater storage can also reduce conventional back-up energy use, though it may also increase space requirements. One of the most significant benefits of HPWHs is their ability to produce two to three times more heat output energy per unit of input energy than standard resistance and fossil-fueled water heaters. They do this by using a small amount of conventional energy (e.g., electricity, fossil fuel) to move and upgrade the temperature of a much larger amount of low-temperature energy. An air-source HPWH also provides potentially useful supplemental air cooling and dehumidification for occupants, which should be taken into account when defining the energy balance for the application. Cooling output should be directed to provide occupant comfort or other benefit and avoid interfering with temperature-sensitive equipment (EPRI 1990).

Demand-controlled water heating can significantly reduce the cost of heating water electrically. Demand controllers operate on the principle that a building's peak electrical demand exists for a short period, during which heated water can be supplied from storage rather than through additional energy applications. Shifting the use of electricity for service water heating from peak demand periods allows water heating at the lowest electric energy cost in many electric rate schedules. The building electrical load must be detected and compared with peak demand data. When the load is below peak, the control device allows the water heater to operate. Some controllers can program deferred loads in steps as capacity is available. The priority sequence may involve each of several banks of elements in (1) a water heater, (2) multiple water heaters, or (3) water-heating and other equipment having a deferrable load, such as pool heating and snow melting. When load controllers are used, hot-water storage must be sized appropriately.

Electric off-peak storage water heating is a water-heating equipment load management strategy whereby electrical demand to a water-heating system is time-controlled, primarily in relation to the building or utility electrical load profile. This approach may require increased tank storage capacity and/or stored-water temperature to accommodate water use during peak periods.

Sizing recommendations in this chapter apply only to water heating without demand or off-peak control. When demand control devices are used, the storage and recovery rate may need to be increased to supply all the hot water needed during the peak period and during the ensuing recovery period. Manian and Chackeris (1974) include a detailed discussion on load-limited storage heating system design.

Indirect Water Heating

In indirect water heating, the heating medium is steam, hot water, or another fluid that has been heated in a separate generator or boiler. The water heater extracts heat through an external or internal heat exchanger.

When the heating medium is at a higher pressure than the service water, the service water may be contaminated by leakage of the heating medium through a damaged heat transfer surface. In the United States, some national, state, and local codes require double-wall, vented tubing in indirect water heaters to reduce the possibility of cross-contamination. When the heating medium is at a lower pressure than the service water, other jurisdictions allow single-wall tubing heaters because any leak would be into the heating medium.

If the heating medium is steam, high rates of condensation occur, particularly when a sudden demand causes an inflow of cold water. The steam pipe and condensate return pipes should be of ample size. Condensate may be cooled by preheating the cold-water supply to the heater.

Corrosion is minimized on the heating medium side of the heat exchanger because no makeup water, and hence no oxygen, is brought into that system. The metal temperature of the service water side of the heat exchanger is usually less than that in direct-fired water heaters. This minimizes scale formation from hard water.

Storage water heaters (see also the section on Water-Heating Terminology) are designed for service conditions where hot-water requirements are not constant (i.e., where a large volume of heated water is held in storage for periods of peak load). The amount of storage required depends on the load's nature and water heater's recovery capacity. An individual tank or several tanks joined by a manifold may be used to provide the required storage.

External storage water heaters are designed for connection to a separate tank (Figure 12). Boiler water circulates through the heater shell, while service water from the storage tank circulates through the tubes and back to the tank. Circulating pumps are usually installed in both the boiler water piping circuit and the circuits between the heat exchanger and the storage tank. Steam can also be used as the heating medium in a similar scheme.

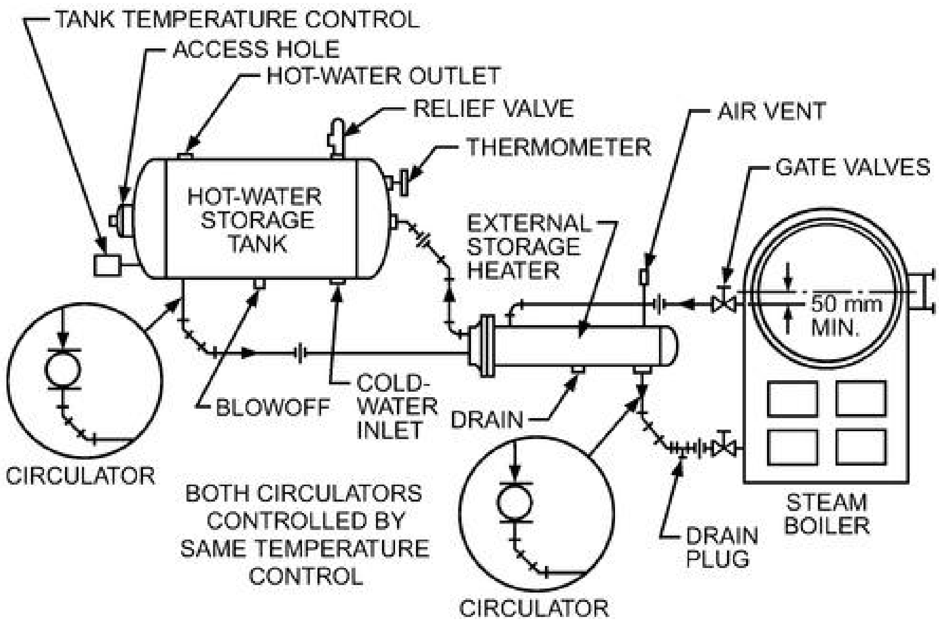

Figure 12. Indirect, External Storage Water Heater

Instantaneous indirect water heaters (tankless coils) are best used for a steady, continuous supply of hot water. In these units, the water is heated as it flows through the tubes. Because the heating medium flows through a shell, the ratio of hot-water volume to heating medium volume is small. As a result, variable flow of the service water causes uncertain temperature control unless a thermostatic mixing valve is used to maintain the hot-water supply to the plumbing fixtures at a more uniform temperature.

Some indirect instantaneous water heaters are located inside a boiler. The boiler is provided with a special opening through which the coil can be inserted. Although the coil can be placed in the steam space above the water line of a steam boiler, it is usually placed below the water line. The water heater transfers heat from the boiler water to the service water. The gross output of the boiler must be sufficient to serve all loads.

Semi-Instantaneous

These water heaters have limited storage to meet the average momentary surges of hot-water demand. They usually consist of a heating element and control assembly devised for close control of the temperature of the leaving hot water.

Circulating Tank

These water heaters are instantaneous or semi-instantaneous types used with a separate storage tank and a circulating pump. The storage acts as a flywheel to accommodate variations in the demand for hot water.

Blending Injection

These water heaters inject steam or hot water directly into the process or volume of water to be heated. They are often associated with point-of-use applications (e.g., certain types of commercial laundry, food, and process equipment). *Caution*: Cross contamination of potable water is possible.

Solar

Availability of solar energy at the building site, efficiency and cost of solar collectors, system installation costs, and availability and cost of other fuels determine whether solar energy collection units should be used as a primary heat energy source. Solar energy equipment can also be included to supplement other energy sources and conserve fuel or electrical energy.

The basic elements of a solar water heater include solar collectors, a storage tank, piping, controls, and a transfer medium. The system may use natural or forced circulation. Auxiliary heat energy sources may be added, if needed.

Collector design must allow operation in below-freezing conditions, where applicable. Antifreeze solutions in a separate collector piping circuit arrangement are often used, as are systems that allow water to drain back to heated areas when low temperatures occur. Uniform flow distribution in the collector or bank of collectors and stratification in the storage tank are important for good system performance.

Application of solar water heaters depends on (1) auxiliary energy requirements; (2) collector orientation; (3) temperature of the cold water; (4) general site, climatic, and solar conditions; (5) installation requirements; (6) area of collectors; and (7) amount of storage. Chapter 36 has more detailed design information.

Wood Fired

Water heaters are available that use wood, usually in chip or pellet form, as the fuel source.

Waste Heat Use

Waste heat recovery can reduce energy cost and the energy requirement of the building heating and service water-heating equipment. Waste heat can be recovered from equipment or processes by using appropriate heat exchangers in the hot gaseous or liquid streams. Heat recovered is frequently used to preheat water entering the service water heater. A conventional water heater is typically required to augment the output of a waste heat recovery device and to provide hot water during periods when the host system is not in operation.

Refrigeration Heat Reclaim

These systems heat water with heat that would otherwise be rejected through a refrigeration, air-conditioning, or heat pump condenser. Refrigeration heat reclaim uses refrigerant-to-water heat exchangers connected to the refrigeration circuit between the compressor and condenser of a host refrigeration or air-conditioning system to extract heat. Water is heated only when the host is operating. Because many simple systems reclaim only superheat energy from the refrigerant, they are often called **desuperheaters**. However, some units are also designed to provide partial or full condensing. The refrigeration heat reclaim heat exchanger is generally of vented, double-wall construction to isolate potable water from refrigerant. Some heat reclaim devices are designed for use with multiple refrigerant circuits. Controls are required to limit high water temperature, prevent low condenser pressure, and provide for freeze protection. Refrigeration systems with higher run time and lower efficiency provide more heat reclaim potential. Most systems are designed with a preheat water storage tank connected in series with a conventional water heater (EPRI 1992). In all installations, care must be taken to prevent inappropriately venting refrigerants.

Combination Heating

A **combination system** (**combo** or **combi system**) provides hot water for both space heating and domestic use. Most combi systems are one of two types. The first type consists of a water-heating source and a hydronic air handler with a space-heating coil. A space-cooling coil is often included with the air handler to provide year-round comfort. The second type consists of a hydronic space heater with a domestic hot-water loop. The domestic hot-water loop uses an integrated heat exchanger with or without an indirect storage tank. Combi systems can also be subdivided into segregated and nonsegregated systems. A segregated system keeps the potable hot water separate from the fluid used in the heat exchange circuit for space heating, through the installation of additional heat exchangers and pumps if required. A nonsegregated system uses potable hot water to serve both the space-heating circuit and domestic hot-water system. In nonsegregated systems, a means to prevent water stagnation is required; this often involves pumping the water around the circuit or flushing the circuit at regular intervals.

The benefits of combi systems include (1) cost reductions through the use of one heat generator and one vent system, (2) space savings in most applications through having a packaged system delivering more than one function, and (3) efficiency benefits through the use of advanced controls in select systems that can optimize the combi system operation.

A method of testing combi systems is given in ASHRAE *Standard* 124. The test procedures allow the calculation of combined annual efficiency (CAE), as well as space- and water-heating efficiency factors. Kweller (1992), Pietsch and Talbert (1989), Pietsch et al. (1994), Subherwal (1986), and Talbert et al. (1992) provide additional design information on noncondensing combi systems. Butcher (2011), Schoenbauer et al. (2012), and Thomas (2011) provide guidance for condensing combi systems.

8. BUILDING APPLICATIONS

Service hot water may be used in various ways in residential, commercial, institutional, and industrial buildings. In some buildings, such as retail stores and office buildings, hot water is predominately used at lavatory sinks for hand washing and, to a lesser amount, at service sinks for floor-cleaning purposes. In other commercial and institutional buildings, hot-water use is process dominated for operations such as commercial kitchens, laundry, and manufacturing, while hot-water use is minimal for hand washing. Residential facilities use hot water in their kitchen, bathroom, and laundry, and the usage is more balanced. The following section identifies some of the common types of facilities that use service hot water. Each facility type is characterized in terms of type of hot-water use, and metrics are provided for average and peak hot-water use.

Dormitories. Hot-water requirements for college dormitories generally include showers, lavatories, service sinks, and clothes washers. Peak demand usually results from the use of showers. Load profiles and hourly consumption data indicate that peaks may last 1 or 2 h and then taper off substantially. Peaks occur predominantly in the evening, mainly around midnight. The figures do not include hot water used for food service.

Military Barracks. Design criteria for military barracks are available from the engineering departments of the U.S. Department of Defense. Some measured data exist for hot-water use in these facilities. For published data, contact the U.S. Army Corps of Engineers or Naval Facilities Engineering Command.

Motels. Domestic hot-water requirements are for tubs and showers, lavatories, and general cleaning purposes. Recommendations are based on tests at low- and high-rise motels located in urban, suburban, rural, highway, and resort areas. Peak demand, usually from shower use, may last 1 or 2 h and then drop off sharply. Food service, laundry, and swimming pool requirements are not included.

Nursing Homes. Hot water is required for tubs and showers, wash basins, service sinks, kitchen equipment, and general cleaning. These figures include hot water for kitchen use. When other equipment, such as that for heavy laundry and hydrotherapy purposes, is to be used, its hot-water requirement should be added.

Office Buildings. Hot-water requirements are primarily for cleaning and lavatory use by occupants and visitors. Older office buildings often use hot-water recirculation-loop systems and are thus good candidates for water-heating distribution system efficiency upgrades through more modern controls and/or addition of point-of-use water heaters. Hot-water use for food service in office buildings is not included.

Food Service Facility. Commercial kitchens can be separated into five major stand-alone food service facility types: coffee/specialty, bar/tavern, deli/sandwich, quick-service restaurant, and full-service restaurant. Commercial kitchens are found in eight major facility types, including nursing/residential care, K-12 schools, supermarkets, office buildings, hotels/casinos with kitchens, hospitals, colleges/universities, and correctional facilities. The three largest segments are coffee/specialty shops, quick-service restaurants and full-service restaurants, together roughly accounting for 75% of all commercial kitchens. Hot-water use intensity in facilities can be distinguished by types of wares used in the dining room. Many smaller facilities, such as coffee shops, sandwich shops, and quick-service restaurants, use disposable wares (e.g., plates, cups), and therefore have much lower use intensity, whereas larger facilities, such as full-service restaurants and cafeterias, use reusable wares and utensils. Hot water is used primarily for ware washing (e.g., dishes, cups, cutting boards). Other uses include food preparation, floor and equipment cleaning, and hand washing.

Apartments. Hot-water requirements for both garden-type and high-rise apartments are for one- and two-bath apartments, for showers, lavatories, kitchen sinks, dishwashers, clothes washers, and general cleaning purposes. Clothes washers can be either in individual apartments or centrally located. These data apply to central water-heating systems only.

Elementary Schools. Hot-water requirements are for lavatories, cafeteria and kitchen use, and general cleaning purposes. When showers are used, their additional hot-water requirements should be added. Recommendations include hot water for dishwashers but not for extended school operation such as evening classes.

High Schools. Senior high schools, grades 9 or 10 to 12, require hot water for showers, lavatories, dishwashers, kitchens, and general cleaning. Junior high schools, grades 7 to 8 or 9, have requirements similar to those of senior high schools. Junior high schools without showers follow the recommendations for elementary schools.

Requirements for high schools are based on daytime use. Recommendations do not take into account hot-water use for additional activities, such as night school. In such cases, the maximum hourly demand remains the same, but the maximum and average daily use increase, usually by the number of additional people using showers and, to a lesser extent, eating and washing facilities.

An important consideration in design of water heating and hot water distribution systems in K-12 schools is that schools have low average occupancy levels. Because of holidays, weekends, and other non-use periods (e.g. night), most K-12 schools are unoccupied approximately 75% of all hours of the entire year. This makes use of recirculation loops (RL) range from less desirable to highly undesirable from both energy use and first-cost perspectives in such applications. K-12 schools often both use less energy and have lower first cost if loads are served by multiple smaller water heaters located near end uses, eliminating the need for recirculation loops (Hiller 2002, 2005c; Hiller et al. 2002, 2004).

9. HOT-WATER LOAD AND EQUIPMENT SIZING

Whatever the hot-water use pattern and resultant hot-water load profile versus time, there will always be a **design hot-water use load profile curve** condition that the system should be sized to satisfy. It is important to recognize that all hot-water loads can be served by multiple different combinations of heating rate and storage volume; there is not just one sizing solution (Hiller 1998). For example, if little or no hot-water storage is provided (e.g., tankless water heater), a heating rate high enough to meet the highest instantaneous hot-water load must be provided. As larger amounts of storage are provided, needed heating rates become smaller.

To serve hot-water load adequately, the needs of both the peak energy withdrawal rate (i.e., the highest hot-water flow rate expected combined with the lowest entering cold-water temperature expected) and total integrated daily energy delivery must be met. Peak energy withdrawal rates can be met either by providing the energy in real time as the draw occurs, by withdrawing previously heated water from storage, or both.

The smallest heating rate that will work for a given system is a rate that can just heat the total amount of hot water used under the design load profile in 24 h. That does not mean, however, that the storage volume needed is the total 24 h design load profile hot-water used. Since heating will be ongoing throughout the day, there will be a significantly smaller needed storage volume than total daily hot water volume used. (Hiller and Johnson, 2015, 2017a, 2017b)

When sizing hot-water systems it is possible to create a design/sizing curve for the design hot-water load profile, showing needed heating rate versus provided storage volume. This is true for all hot-water systems. Ways to create the design hot-water use load profile curves for sizing are discussed in this chapter and in several ASHRAE technical papers (Hiller and Johnson, 2015, 2017a, 2017b). Providing a heating rate higher than necessary for a selected storage volume just means the run-time of the heating device will be reduced and its number of on-off heating cycles will increase compared to using an appropriate heating rate (or the heat input rate must be otherwise modulated downward to avoid overheating, which would also reduce on-off cycling). This happens because the higher than necessary heating rate reheats storage faster and forces the system to turn off. Similarly, providing more than necessary storage for a given heating rate just increases system costs and heat loss. The excess storage volume either cannot be reheated, or never gets used (Hiller 1998). The biggest challenge to properly sizing water heating systems is providing good estimates of design hot water use load profile curves (i.e., cumulative hot-water demand profiles versus time interval for various applications).

Sizing Methods

This chapter presents three different water heating system sizing strategies. Two of the sizing strategies (the **Hunter curve/fixture units method** and the **fixture count** method) were both developed to apply only to systems using very high heating rates, intended to heat the demanded hot-water mostly real time as it is drawn, as do instantaneous water heaters (having greater than 300 W/L of storage), and hence provide only a single combination of heating rate and storage volume for sizing purposes. The other sizing techniques presented all use some form of what can generically be described as **cumulative volume versus time interval (CV*dt*)** analysis (Hiller and Johnson 2015, 2016a, 2016b, 2016c, 2017a, 2017b; Werner and Spielvogel 1969a, 1969b), and are thus capable of producing curves of needed heating rate versus storage volume.

Methods of determining cumulative volume versus time interval curves have evolved and improved as improved field test data collection equipment and analysis techniques have become available. Briefly, the CV*dt* analysis determines from field test data on a given building type the maximum total cumulative hot water used over increasing large time durations, allowing the production of peak cumulative volume versus time interval curves for system sizing purposes. Hot-water use time diversity is inherently built into CV*dt* curves (i.e., is actually measured rather than hot-water use time coincidence/diversity being assumed as in older sizing methods), and they are easily produced during data analysis. No additional correction factors or safety factors need to be applied to the CV*dt* curves, since the peak CV*dt* curve is already the worst-case condition (assuming data was collected over a long enough time period, [e.g., 12 mo] to ensure the peak day is represented in the data). However, one can still provide some sorts of safety factors if desired.

The Hunter curve/fixture units and fixture count methods were developed from limited data collected long ago (1920s to 1940s), long before the existence of water and energy-efficient fixtures and appliances, and long before short data collection time intervals and automated data collection equipment were available. As a result, those methods tend to produce substantially oversized systems when using modern fixtures and appliances because higher-than-what-actually-happens coincidences of hot-water use are assumed and wide safety factors are also applied. These sizing techniques remain in the chapter because there is as yet no newer data with which to size systems in certain building types. Modernized versions of these sizing methods are under development using modern fixture and appliance flow requirements.

Sizing methods that collect information on fixture and appliance hot-water flow rates and volumes and then assume some time-coincidence of use factor, load factor, or diversity factor, such as the Hunter curve/fixture unit and fixture count methods and their modernized variants, are much less expensive and easier to develop than CV*dt* sizing methods because data collection requirements are minimal. The benefit of the CV*dt* sizing approach is that one does not have to assume amounts of time coincidence of use; one simply measures it during field testing for various water-heating applications. It is hoped that as more field testing of water-heating systems is done, the more engineers who know how to determine CV*dt* information from field test data, the greater the number and variety of water heating applications for which CV*dt* data is available will be, thus reducing the need for assuming system sizing answers when making assumptions about hot water use time coincidence.

Load Diversity

The greatest difficulty in designing water-heating systems comes from uncertainty about design hot-water loads, especially for buildings not yet built. Although it is fairly simple to test maximum flow rates of various hot-water fixtures and appliances, actual flow rates and durations are user-dependent. Moreover, the timing of different hot-water use events varies from day to day, with some overlap, but almost never will all fixtures be used simultaneously. As the number of hot-water-using fixtures and appliances grows, the percent of those fixtures used simultaneously decreases.

The older hot-water load information in this chapter is based on limited-scale field testing combined with statistical analysis to estimate load demand or **diversity** factors (percent of total possible hot-water use that ever actually occurs at one time) versus number of end use points, number of people, etc. Much of the work to provide these diversity factors dates from the 1930s to the 1960s and is therefore outdated; it remains, however, the best information currently available for some building types (with a few exceptions, as noted). Of great concern is the fact that most of the data from those early studies were for fixtures that used water at much higher flow rates than modern energy-efficient fixtures (e.g., low-flow shower heads and sink aerators, energy-efficient washing machines and dishwashers). Some research has provided limited information on hot-water use by more modern fixtures, and on their use diversity (Becker et al. 1991; Buchberger, et.al. 2015; Goldner 1994a, 1994b; Goldner and Price 1999; Hiller 1998; Hiller and Johnson 2015; Hiller and Lowenstein 1996, 1998; Thrasher and DeWerth 1994), but much more information in a variety of applications is needed before design procedures can be updated for a greater range of applications. Using the older load diversity information usually results in a water-heating system that adequately serves the loads, but often results in substantial oversizing (oversizing by a factor of 10 or more has been seen in some installations). Oversizing can be a deterrent to using modern high-efficiency water-heating equipment, which may have higher first cost per unit of capacity than less efficient equipment. Sustainable design must consider these effects.

Hot- and Cold-Water Temperatures Important to System Sizing

Knowledge of entering cold- and desired hot-water delivery temperatures is critical to correct sizing of water-heating equipment.

Entering cold-water temperatures are application specific and vary with geographic location, season, and type of water source (surface, well, municipal, snow melt, etc.) Entering cold-water temperature information can usually be obtained from local water service providers or county agricultural services (well water). It is also available in some form from the U.S. Geological Survey, National Weather Service, and other sources. Plots of average groundwater, ground, and air temperatures versus geographic location are contained in some building codes. Lacking more specific information, entering cold-water temperature can be estimated from daily average air temperature information: temperatures of water exiting underground piping are usually somewhere around average daily air temperature, but lag the air temperatures by 1 to 2 months.

Table 3 Typical Residential Use of Hot Water

Use	High Flow, Litres/Task	Low Flow (Water Savers Used), Litres/Task	UltralowFlow, Litres/Task
Food preparation	19	11	11
Hand dish washing	15	15	11
Automatic dishwasher	57	57	11 to 38
Clothes washer	121	80	19 to 57
Shower or bath	76	57	38 to 57
Face and hand washing	15	8	4 to 8

Seasonal coldest entering water temperature is 0°C in some cold locations, where the water does not freeze because it is moving. Seasonal hottest cold-water temperature for water exiting underground piping is around 29 to 32°C in hot regions of the United States, but can be even hotter if piping is exposed to the air or sun.

Hot-water delivery temperature is a design parameter to be specified by the system designer. ASHRAE *Guideline* 12-2020 discusses impacts of hot- and cold-water temperatures, especially on potential for pathogen growth.

Residential

Table 3 shows typical hot-water usage in a residence, including usage rates of modern ultralow-use appliances and fixtures. It is more difficult to show typical values for newer devices, because some automatically adjust the amount of hot water they use based on sensed load or cycle setting. The "high flow" values in Table 3 represent older equipment and fixtures. In its *Minimum Property Standards for Housing*, the U.S. Department of Housing and Urban Development (HUD 1994) established minimum permissible water heater sizes (Table 4). Storage water heaters may vary from the sizes shown if combinations of recovery and storage are used that produce the required 1 h draw.

Table 4 HUD-FHA Minimum Water Heater Capacities for One- and Two-Family Living Units

Number of Baths	1 to 1.5			2 to 2.5				3 to 3.5			
Number of Bedrooms	**1**	**2**	**3**	**2**	**3**	**4**	**5**	**3**	**4**	**5**	**6**
Gas[a]											
Storage, L	76	114	114	114	150	150	190	150	190	190	190
kW input	7.9	10.5	10.5	10.5	10.5	11.1	13.8	11.1	11.1	13.8	14.6
1 h draw, L	163	227	227	227	265	273	341	273	311	341	350
Recovery, mL/s	24	32	32	32	32	36	42	34	34	42	44
Electric[a]											
Storage, L	76	114	150	150	190	190	250	190	250	250	300
kW input	2.5	3.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1 h draw, L	114	167	220	220	273	273	334	273	334	334	387
Recovery, mL/s	10	15	19	19	23	23	23	23	23	23	23
Oil[a]											

Storage, L	114	114	114	114	114	114	114	114	114	114	114
kW input	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1 h draw, L	337	337	337	337	337	337	337	337	337	337	337
Recovery, mL/s	62	62	62	62	62	62	62	62	62	62	62
Tank-type indirect[b,c]											
I-W-H-rated draw, L in 3 h, 55 K rise		150	150		250	250[e]	250	250	250	250	250
Manufacturer-rated draw, L in 3 h, 55 K rise		186	186		284	284[e]	284	284	284	284	284
Tank capacity, L		250	250		250	250[e]	310	250	310	310	310
Tankless-type indirect[c,d]											
I-W-H-rated draw, mL/s, 55 K rise		170	170		200	200[e]	240	200	240	240	240
Manufacturer-rated draw, L in 5 min, 55 K rise		57	57		95	95[e]	133	95	133	133	133

Note: Applies to tank-type water heaters only.

[a] Storage capacity, input, and recovery requirements indicated are typical and may vary with manufacturer. Any combination of requirements to produce stated 1 h draw is satisfactory.

[b] Boiler-connected water heater capacities (82°C boiler water, internal or external connection).

[c] Heater capacities and inputs are minimum allowable. Variations in tank size are permitted when recovery is based on 4.2 mL/(s · kW) at 55 K rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot-water heaters.

[d] Boiler-connected heater capacities (93°C boiler water, internal or external connection).

[e] Also for 1 to 1.5 baths and 4 bedrooms for indirect water heaters.

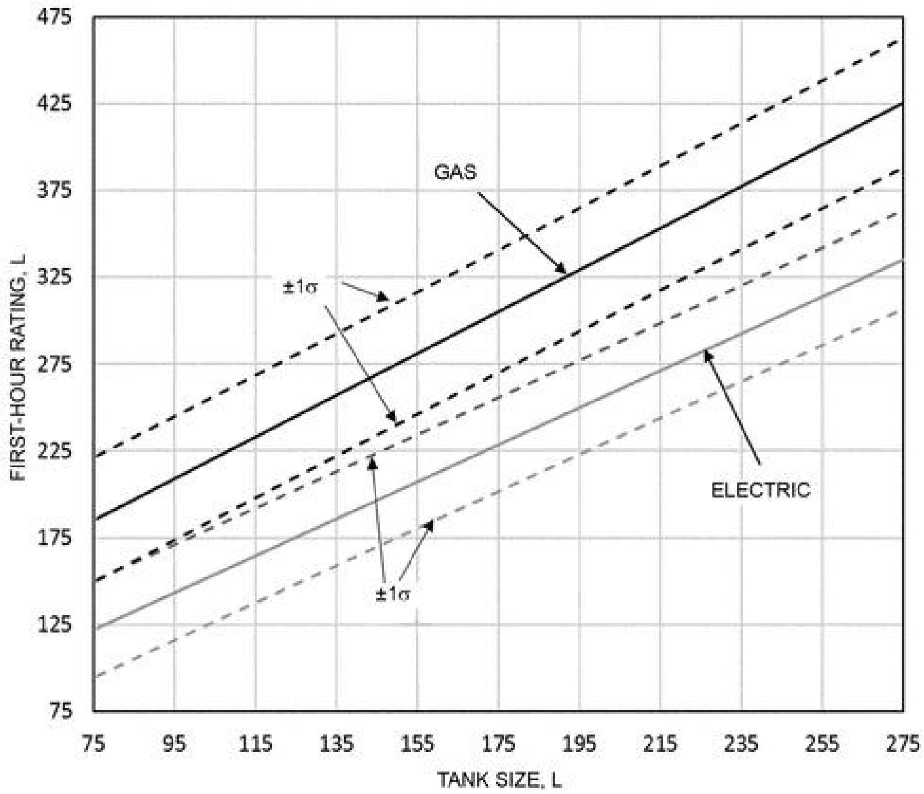

Figure 13. First-Hour Rating (FHR) Relationships for Residential Water Heaters

Table 5 Overall (OVL) and Peak Average Hot-Water Use

	Average Hot-Water Use, L							
	Hourly		Daily		Weekly		Monthly	
Group	**OVL**	**Peak**	**OVL**	**Peak**	**OVL**	**Peak**	**OVL**	**Peak**
All families	9.8	17.3	236	254	1652	1873	7178	7700
"Typical" families	9.9	21.9	239	252	1673	1981	7270	7866

The first-hour rating (FHR) is a measure of the maximum amount of hot water that a water heater can supply in 1 h of operation when started from operational temperature under specific test conditions (DOE 2014). The linear regression lines shown in Figure 13 represent the FHR for the most common sizes and heating rates of 45 electric heaters (both resistance and heat pump) and 150 gas heaters (DOE 2017). Regression lines are not included for oil-fired heaters because of limited data. The FHR represents water-heater performance characteristics that are similar to those represented by the 1 h draw values listed in Table 4. Residential water-heating equipment sizing is frequently driven by amounts of water used over periods of considerably less than 1 h, often as short as 15 minutes (Hiller 1998). Over these short periods, storage tank volume is a better indicator of hot-water delivery capability than FHR for residential applications. Water heater FHRs changed (generally become lower) because of changes in the DOE test and rating conditions that went into effect in 2015.

Another factor to consider when sizing water heaters is the set-point temperature. At lower storage tank water temperatures, the tank volume and/or energy input rate may need to be increased to meet a given hot-water demand. Currently, manufacturers ship residential water heaters with a recommendation that the initial set point be approximately 50°C to minimize the potential for scalding. Reduced set points generally lower standby losses and increase the water heater’s efficiency and recovery capacity, but may also reduce the amount of hot water available.

The structure and lifestyle of a typical family (variations in family size, age of family members, presence and age of children, hot-water use volume and temperature, and other factors) cause hot-water consumption demand patterns to fluctuate widely in both magnitude and time distribution.

Perlman and Mills (1985) developed the overall and peak average hot-water use volumes shown in Table 5. Average hourly patterns and 95% confidence level profiles are shown in Figures 14 and 15. Samples of results from the analysis of similarities in hot-water use are given in Figures 16 and 17.

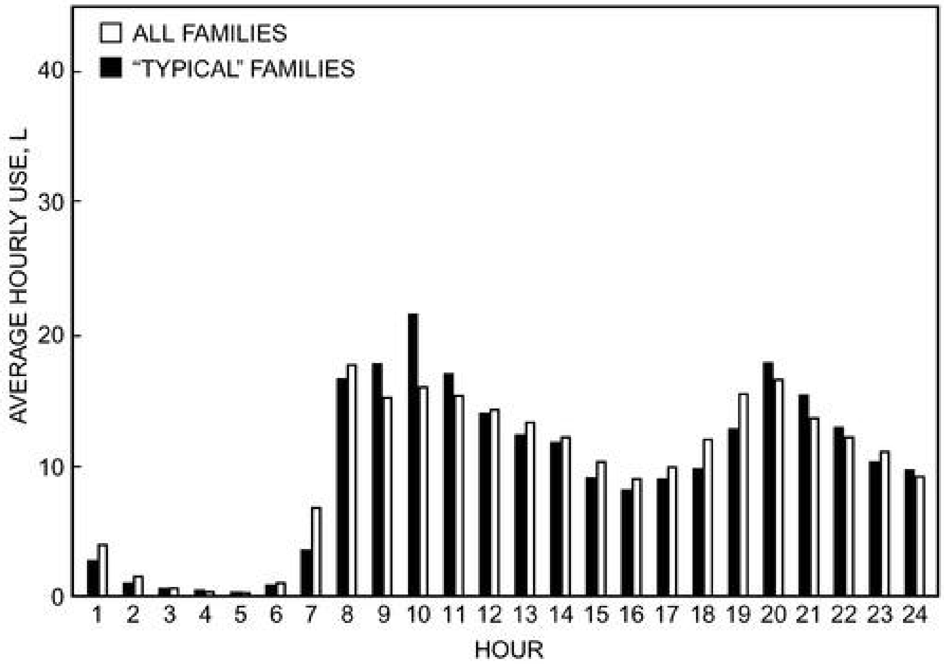

Figure 14. Residential Average Hourly Hot-Water Use

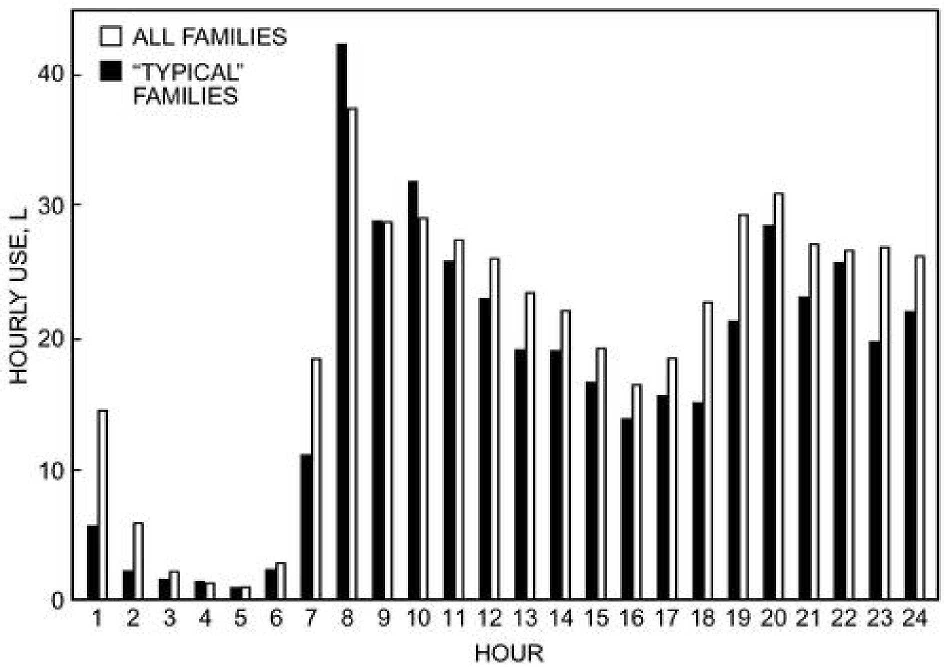

Figure 15. Residential Hourly Hot-Water Use, 95% Confidence Level

Commercial and Institutional

Most commercial and institutional establishments use hot or warm water. The specific requirements vary in total volume, flow rate, duration of peak load period, and temperature. Water heaters and systems should be selected based on these requirements.

This section covers sizing recommendations for central storage water-heating systems. Hot-water usage data and sizing curves for dormitories, motels, nursing homes, office buildings, food service establishments, apartments, and schools are based on EEI-sponsored research, which used a cumulative volume versus time interval analysis for producing heating rate versus storage volume curves (Werden and Spielvogel 1969a, 1969b). Caution must be taken in applying these data to small buildings. Also, within any given category there may be significant variation. For example, the motel category encompasses standard, luxury, resort, and convention motels.

When additional hot-water requirements exist, increase the recovery and/or storage capacity accordingly. For example, if there is food service in an office building, the recovery and storage capacities required for each additional hot-water use should be added when sizing a single central water-heating system. The motel data of Figure 26 does not include food service hot-water loads and loads due to large meetings. It is unclear to what extent laundry hot-water loads are included in the motel data, so it is wise to assume laundry loads are not included and must be added if laundry loads are to be served.

Peak hourly and daily demands for various categories of commercial and institutional buildings are shown in Table 6. These demands for central-storage hot water represent the maximum flows metered in this 129-building study, excluding extremely high and very infrequent peaks. Table 6 also shows average hot-water consumption figures for these buildings. Averages for schools and food service establishments are based on actual days of operation; all others are based on total days. These averages can be used to estimate monthly consumption of hot water, but are not intended for sizing purposes because they do not show the time distribution of draws.

Research conducted for ASHRAE (Becker et al. 1991; Thrasher and DeWerth 1994) and others (Goldner 1994a, 1994b) included a compilation and review of service hot-water use information in commercial and multifamily structures along with new monitoring data. Some of this work found consumption comparable to those shown in Table 6; however, many of the studies showed higher consumption.

Specific Applications Design and Sizing

Fast Food Restaurants. Hot water is used for food preparation, cleanup, and rest rooms. Dish washing is usually not a significant load. In most facilities, peak usage occurs during the cleanup period, typically soon after opening and immediately before closing. Hot-water consumption varies significantly among individual facilities. Fast food restaurants typically consume 1000 to 2000 L per day (EPRI 1994).

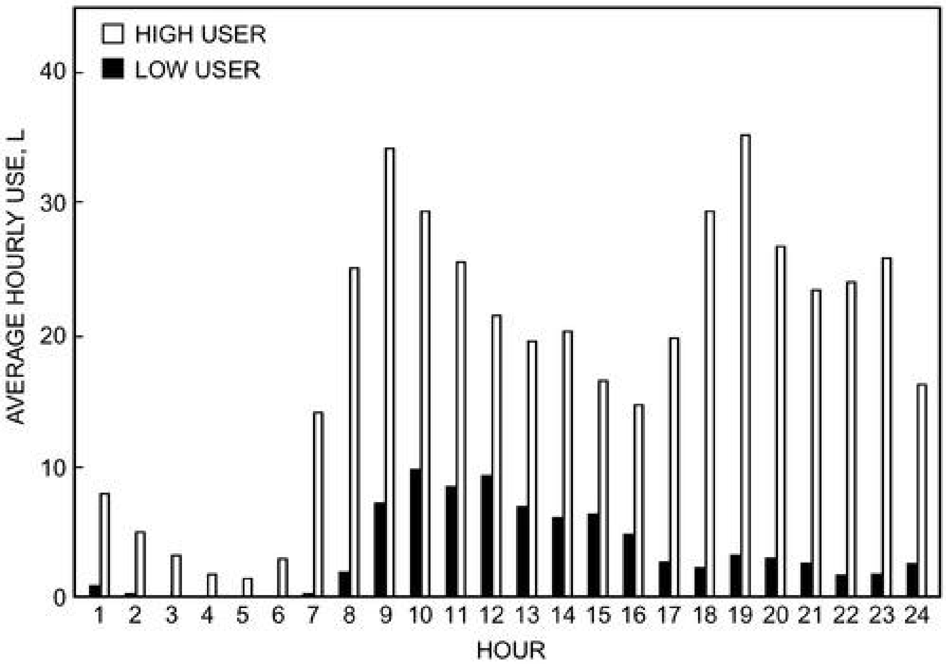

Figure 16. Residential Average Hourly Hot-Water Use Patterns for Low and High Users

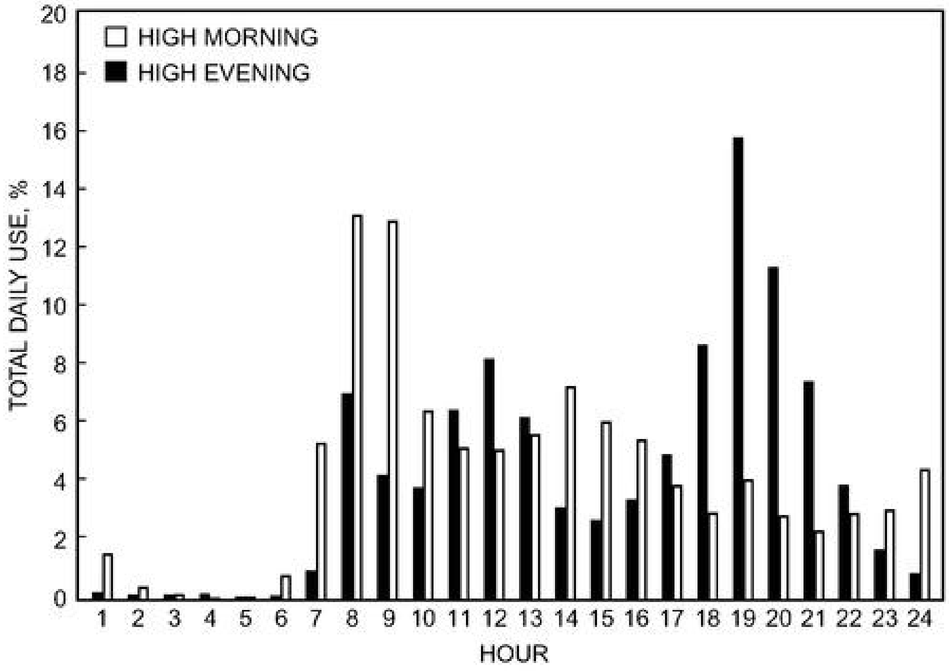

Figure 17. Residential Hourly Hot-Water Use Pattern for Selected High Morning and High Evening Users

Supermarkets. The trend in supermarket design is to incorporate food preparation and food service functions, substantially increasing the usage of hot water. Peak usage is usually associated with cleanup periods, often at night, with a total consumption of 1100 to 3800 L per day (EPRI 1994).

Table 6 Hot-Water Demands and Use for Various Types of Buildings[*]

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	14.4 L/student	83.3 L/student	49.7 L/student
Women's dormitories	19 L/student	100 L/student	46.6 L/student
Motels: Number of units[a]			
20 or less	23 L/unit	132.6 L/unit	75.8 L/unit
60	20 L/unit	94.8 L/unit	53.1 L/unit
100 or more	15 L/unit	56.8 L/unit	37.9 L/unit
Nursing homes	17 L/bed	114 L/bed	69.7 L/bed
Office buildings	1.5 L/person	7.6 L/person	3.8 L/person
Food service establishments:			
Type A: Full-meal restaurants and cafeterias	5.7 L/max meals/h	41.7 L/max meals/day	9.1 L/average meals/day[b]
Type B: Drive-ins, grills, luncheonettes, sandwich and snack shops	2.6 L/max meals/h	22.7 L/max meals/day	2.6 L/average meals/day[b]
Apartment houses: Number of apartments			
20 or less	45.5 L/apartment	303.2 L/apartment	159.2 L/apartment
50	37.9 L/apartment	276.7 L/apartment	151.6 L/apartment
75	32.2 L/apartment	250 L/apartment	144 L/apartment
100	26.5 L/apartment	227.4 L/apartment	140.2 L/apartment
200 or more	19 L/apartment	195 L/apartment	132.7 L/apartment
Elementary schools	2.3 L/student	5.7 L/student	2.3 L/student[b]
Junior and senior high schools	3.8 L/student	13.6 L/student	6.8 L/student[b]

[*] Data predate modern low-flow fixtures and appliances.
[a] Interpolate for intermediate values.
[b] Per day of operation.

Apartments. Table 7 shows cumulative hot-water use over time for apartment buildings for different occupant demographics, taken from a series of field tests by Becker et al. (1991), Goldner (1994a, 1994b), Goldner and Price (1999), and Thrasher and DeWerth (1994). These data already include use diversity information, and enable use of modern water-heating equipment sizing methods for this building type, making it easy to understand the variety of heating rate and storage volume combinations that can serve a given load profile (see Example 1). Unlike Table 6, Table 7 presents low/medium/high (LMH) guidelines rather than specific singular volumes, and gives better time resolution of peak hot-water use information. The same information is shown graphically in Figure 18. Note that these studies showed that occupants on average use more hot water when water-heating costs are included in the rent, than if the occupants pay directly for water-heating energy use.

The low-use peak hot-water consumption profile represents the overall average highest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- All occupants working
- One person working, while one stays at home
- Seniors
- Couples
- Middle income
- Higher population density

The medium-use peak hot-water consumption profile represents the overall average highest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- Families
- Singles
- On public assistance
- Single-parent households

Table 7 Hot-Water Demand and Use Guidelines for Apartment Buildings (Litres per Person at 49°C Delivered to Fixtures)

	Peak Minutes							
Guideline	**5**	**15**	**30**	**60**	**120**	**180**	**Maximum Daily**	**Average Daily**
Low	1.5	3.8	6.4	10.6	17.0	23.1	76	53
Medium	2.6	6.4	11.0	18.2	30.3	41.6	185	114
High	4.5	11.4	19.3	32.2	54.9	71.9	340	204

The high-use peak hot-water consumption profile represents the highest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- High percentage of children
- Low income
- On public assistance
- No occupants working
- Families
- Single-parent households

In applying these guidelines, the designer should note that a building may outlast its current use. This may be a reason to increase the design capacity for domestic hot water or allow space and connections for future enhancement of the service hot-water system. Building management practices, such as the explicit prohibition (in the lease) of apartment clothes washers or the existence of bath/kitchen hook-ups, should be factored into the design process. A diversity factor that lowers the probability of coincident consumption should also be used in larger buildings.

The information in Table 7 and Figure 18 generates a water-heating equipment sizing method for apartment buildings. The cumulative total hot-water consumption versus time interval (which includes all necessary load diversity information) can be used to select a range of heating rate and storage volume options, all of which will satisfy the load. How cumulative volume versus time interval information is used to size water heating systems is somewhat different for water heating systems that use near-inlet-end/bottom-up/multi-pass heating as opposed to near-outlet-end/top-down/single-pass heating.

For bottom-up heating approaches the key is that plots of cumulative total hot-water consumption versus time interval as shown in Figure 18 also represent, by the slope of a line drawn from zero time through the cumulative volume used at any given time, the average hot-water flow rate up to that time interval. Up to any time interval, the minimum average heating rate needed to satisfy the load is one that can heat the average hot-water flow rate through that time duration from the local entering cold-water temperature to the water-heating system delivery temperature and the storage volume needed is the cumulative volume at the selected time interval.

For top-down heating approaches the needed heating rate is more correctly determined by the local slope of the cumulative volume versus time interval curve, not the average slope. This is because top-down heating systems can continue to provide heated water directly to the load without needing to reheat storage once depleted as long as the local slope heating rate is provided. The combination of storage plus real-time heating can supply needed hot water up to the time interval and cumulative volume where the local slope is determined, and at time intervals beyond that the heating rate provided can directly supply hot water to the load by itself.

Eventually, however, storage needs to be reheated, which must also be considered. See the two methods shown in Example 1,where one sizing is for bottom-up heating and the other is for top-down heating. The storage volume needed for bottom-up heating is the total cumulative flow through the time interval over which the average flow rate is determined. (Hiller 1998). To evaluate the range of minimum required heating rates and their corresponding minimum required storage tank volumes, it is easiest to pick various volumes in Figure 18 or Table 7, then determine the heating rate and time period that correspond to them, as shown in Example 1. Final selection of water-heating system heating rate and storage size is then made by examining the first and operating costs of the various combinations.

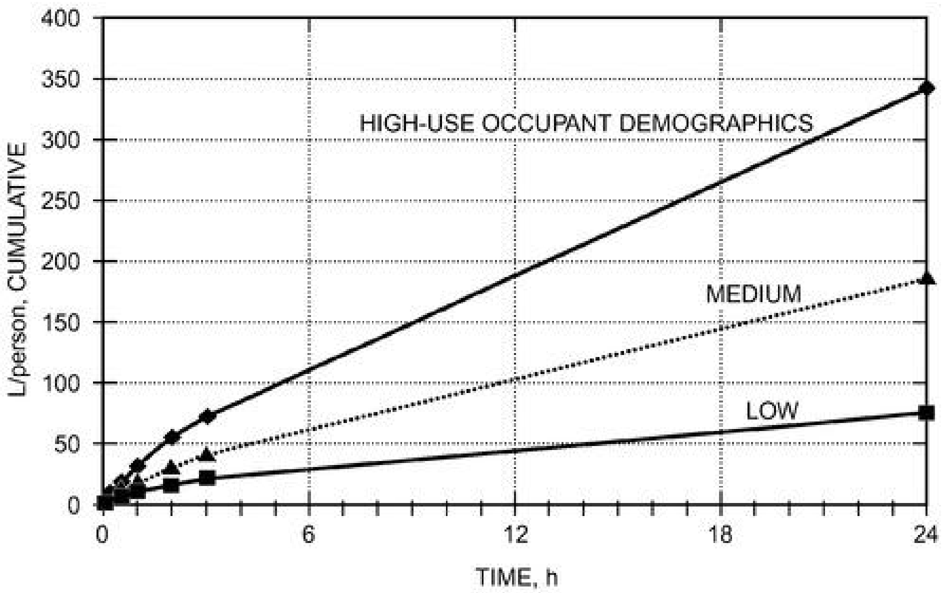

Figure 18. Apartment Building Cumulative Hot-Water Use Versus Time (from Table 7)

Hotels. Hotel hot-water uses tend to be grouped into three major categories: (1) guest room circuit, (2) laundry circuit, and (3) food service/commercial kitchen circuit, with one or more of these circuits served by a water-heating system. Note, however, that while these three hot-water uses may be loads the water-heating circuit was designed and sized to meet, they are often not the only loads served by those circuits. All water-heating circuits have periods of low use for their primary purpose (e.g., little bathing occurs in the middle of the night), allowing them to be used to serve other loads that they were not necessarily sized to serve. One such "not sized for" hot-water load sometimes seen is pool and spa refilling.

Guest room circuits tend to have the following hot water loads: (1) guest showers and baths, (2) guest room sink use, (3) guest room cleaning, and (4) common area cleaning. Bathing (showers and baths) is the largest single hotel hot-water use category, often exceeding all other hot-water uses combined. ASHRAE-funded research project RP-1544 results (Hiller and Johnson 2015, 2016a, 2016b, 2016c, 2017a, 2017b) present findings on a study of a medium-sized conference hotel and a roadside travel hotel. The work provides guidance on sizing of the water heating system, including storage volumes and heating rates of water heaters, based on these two studies. Copies of RP-1544 reports are available from ASHRAE.

The following brief information and example provide an introduction to using the cumulative volume versus time interval (CV*dt*) curves from the RP-1544 research for sizing to serve the guest room circuit of a hotel or motel. Keep in mind that loads on that circuit are assumed to be primarily guest room bathing plus small amounts for guest room sink use and guest room cleaning. Small amounts of common area cleaning loads are also included (i.e., not major cleaning loads like might exist in a large conference hotel). These qualifications mean that the guest room circuit hot-water load curves presented here are bathing dominated.

RP-1544 found that guest room/main hot-water circuits, laundry circuits, and food-service circuits are all characterized by two different categories of hot water use (a finding not generally recognized in earlier research). One category has flow characteristics proportional to the number of guests staying in the hotel. The other category has hot-water use that seems to be independent of hotel occupancy, referred to as baseload or variable hot-water use.

Baseload/variable hot-water use on main/guest room hot-water circuits tends to be caused by routine cleaning operations (that happen every day regardless of hotel occupancy), weather-influenced cleaning (e.g., mopping entry floors during rainy or snowy weather), common area bathroom and other cleaning, and cleaning in support of meetings (e.g., coffee preparation, spill clean-up, floor mopping) that normally only happen on days meetings are held and are attended by potentially different people than hotel guests. As such, baseload/variable hot-water use varies widely from day to day, independent of hotel occupancy, and can be difficult to predict. It appeared from the RP-1544 research that hotel/motels that did not have meeting facilities had much lower design levels of baseload/variable hot-water use than did hotels hosting meetings.

In comparison, the portion of hotel/motel guest room circuit **hot-water use that is proportional to occupancy** is dominated by bathing hot-water use and is reliably predictable. The high-time-resolution hot-water use data that was collected during the RP-1544 research (5 s data collected for over 13 months) enabled the researchers to use advanced data analysis techniques such as flow trace/flow signature analysis to identify almost all individual hot-water draw events as they occurred. This provided the ability to separately identify hot water used for bathing, cleaning, clothes washer/laundry operation, food service, and other less common hot-water uses (e.g., pool and spa filling). The research was then able to produce CV*dt* curves that represent guest room/main circuit, laundry circuit, and commercial kitchen/food service circuits independently of each other. This allows readers the option to size separate hot water systems for each of those load types if desired.

Combined Load Types. The RP-1544 final report and ensuing CV*dt* papers provide guidance on how to combine the different CV*dt* curves when designing hot-water systems that serve various combinations of the three primary hot-water loads. The RP-1544 final report and related technical papers provide guidance on how to determine design hot-water use load profile curve hot-water use curves for both laundry loads and food service, but that information is not presented here for brevity. Refer to the ASHRAE RP-1544 final report and related published ASHRAE technical papers for more information on how to design for and include those water heating loads. Note, moreover, that information in this chapter on hotel/motel hot-water use that predates the RP-1544 research in general either does not include laundry loads, food service loads, or both, or is silent on whether or not the sizing information includes those loads, so it is best to assume those loads are not included in the older data and hence need to be added when sizing systems that serve such loads.

Key Findings from ASHRAE-Sponsored Hotel Field Testing. Below are some key findings from the RP-1544 field test on two hotels of different sizes and types, one a 62-room hotel with no meeting rooms or food service (the “travel” hotel), the other a 242-room hotel having both (the “business” hotel).

- Hotels tend to have three major hot-water use segments: (1) guest room/main circuit, having guest room bathing, sink use and cleaning, and common area cleaning hot-water loads, (2) commercial clothes washer hot-water loads, and (3) commercial kitchen/food service hot-water loads.
- For all three major hot-water use segments, each appeared to have a portion of hot-water use that was proportional to hotel occupancy and a portion that was not (referred to as a baseload/variable hot-water use)
- Baseload hot-water use was highly variable from day to day and difficult to predict. This is because much of what constitutes baseload water use is related to presence or absence of meetings on a given day. For hotels that did not have meeting rooms, baseload hot-water loads were much smaller than for hotels with meeting facilities. One of the reasons meetings have a significant impact on baseload hot-water use is the fact that people attending meetings are not necessarily guests at the hotel, which is partly what makes that kind of load not proportional to hotel occupancy. Although baseload/variable hot-water use is not necessarily proportional to size of common/meeting areas, the volume of baseload/variable hot water used per common floor area for both test hotels was computed to at least provide a starting point for an estimate of baseload/variable hot-water use. For the 62-room hotel (no meeting rooms or food service), baseload/variable hot-water use was computed to be 2.28 L/(day·m^2) and for the 242-room hotel having both meeting rooms and food service, 4.56 L/(day·m^2). More research on what makes baseload hot-water use be what it is would be beneficial.
- Guest room/main water circuit hot-water loads that were proportional to occupancy were very similar between the two hotels tested and are reliably predictable. This is partly because the dominant hot-water use on that circuit is for guest bathing. The RP-1544 field test collected hot-water use information on more than 133,000 bathing events, taken by over 100,000 people, and hence represents probably the largest study of bathing behaviors performed anywhere to date.
- It was determined from having records of hotel guest occupancy every day, plus separate measurements of number of showers every day, and independently from surveys taken at several large conferences, that on average guests bathe once per day, so number of guests = number of bathing events on a given day.
- Guest room sink hot-water use and hot-water use for cleaning the guest rooms was quite low compared to the bathing hot-water loads. Additionally, the majority of bathing events (>95%) were showers. This allowed combining the guest room bathing and cleaning activities into a single use value of 45 L/bathing event. Moreover, showers used an average hot water flow rate of 5.7 L/min, and hence hot water flow during bathing continued for an average of 8 min per shower.
- The peak design-day guest occupancy at both hotels was similar, with the test travel hotel having a peak design-day occupancy of 2.8 guests/room with all rooms occupied, and the test business hotel having a peak design-day occupancy of 2.5 guests/room with all rooms occupied. It is informative to point out that the RP-1544 researchers obtained the original data for the motel hot-water use studies performed by Werden and Spielvogel (W&S) in the 1960s (see Figure 26) in order to compare the two sets of findings. It was determined that the non-dimensionlized CV*dt* curves for motels from the W&S work were very similar in shape and mostly overlapped each other and the non-dimensionalized CV*dt* curves from the RP-1544 work (see Figure 23).
- The largest single difference between the RP-1544 findings and the earlier W&S motel data was that the average room occupancy levels in the W&S work were substantially lower than those found in RP-1544, with average peak day occupancies of 0.95 to 3.5 guests/room, averaging around 1.7 guests/room. It is not possible to determine if the low peak day occupancies of the earlier work were due to short data collection periods (some less than 30 days, 73% less

than 100 days compared to the desirable >365 days) or that perhaps design guest occupancies have gone up compared to years earlier.

- The RP-1544 data showed that 11 to 15% of rooms had simultaneous bathing events under the peak design condition at the two test hotels. Since peak design condition room occupancies were multiple guests per room, and guest rooms normally only had one shower or bath, as guest room occupancy increased beyond one guest per room, the number of simultaneous bathing events increased only slightly. Rather, the time period over which simultaneous bathing events occurred increased, because the bathing events were forced to become ever more sequential instead of simultaneous due to the limit of one bathing facility per guest room. Note that the number or percentage of simultaneous bathing events is not the same as number or percentage of rooms having bathing events in one hour, which is almost 8 times higher. This is because simultaneous bathing events occur over the duration of average bathing events which is around 8 min, rather than 60 min.

- While the guest room/main hot-water circuit hot-water use was dominated by bathing and it was therefore bathing that drove sizing, there were sometimes other large hot-water uses on the guest room circuit. This was because after peak bathing times of day are over (e.g., at night), the water heating system sits nearly idle and thus is available for uses other than bathing (e.g., pool/spa refilling). It appeared that the guest room/main circuits were not specifically sized to serve those other hot water loads, but rather were just used because they were available.

Limitations on the Hotel CV*dt* Curve Bathing-Dominated Hot-Water Load Curves.

- The hotel CV*dt* curves presented here are for hot-water circuits that are bathing dominated, but include small amounts of hot water use for guest room sink use, guest room cleaning, and common area cleaning. They do not include cleaning of large meeting areas or cleaning and servicing areas needed to support large meetings. They also do not include food service or laundry hot-water use.

- For both the W&S motel curves of Figure 26 and the RP-1544 hotel data, the effective diversity factors will decrease as hotel/motel size decreases, and hence the curves become less reliable for sizing when number of guest rooms drops below 10 to 20.

- As hotel/motel size increases, more non-guest-room hot-water loads tend to be served from the same hot-water circuit as the guest rooms, hence the baseload/variable hot-water loads on the circuit can increase substantially. At some size, the guest room circuit can no longer be assumed to be bathing dominated. Since baseload/variable hot-water loads are difficult to predict with current information, it is difficult to know at what hotel/motel size this deviation of the guest room circuit from being bathing dominated will occur. One of the test hotels in the RP-1544 project had 242 guest rooms, so the curves should be reasonably representative at least up to that number of guest rooms.

- Although the bathing portion of hot water use probably remains fairly predictable as hotel/motel size increases, different themed hotel/motels may exhibit significantly different baseload/variable hot water loads (e.g., integrated water-park, vacation/resort)

- One commonly voiced concern is "What if guests all bathe at nearly the same time because of some event?" Experience has shown that while this is theoretically possible, it rarely if ever happens when people are making their own bathing decisions. Only machines behave in such predictable "forced simultaneous draw" ways. In fact, examination of the diversity factors used in some of the older sizing methods in this chapter shows that even under extreme assumptions, no more than about 25% of rooms would be assumed to bathe simultaneously (this compares to 11 to 15% observed in the RP-1544 testing)

Non-Dimensionalized (Normalized) Design Curves: One of the advancements in the CV*dt* sizing approach that came out of the RP-1544 research and related papers is presentation of the design hot-water use load profile curve CV*dt* curves in non-dimensionalized form. This results in there being fewer curves. For example, the motel flow/heat rate versus storage volumes curves of Figure 26 can all be non-dimensionalized by dividing the volume values by the maximum volume shown for each curve and by dividing the flow rate values by the minimum values shown for each curve. When this is done, the three curves are almost on top of each other, allowing use of one curve instead of three different curves to size motels of different sizes (see Figure 23). Non-dimensionalizing in this way results in the curves not being a function of number of rooms or temperatures, except for the way the minimum needed flow/heating rate and 24 h cumulative volumes are computed for any selected project. Moreover, non-dimensionalizing the CV*dt* and related heating rate versus storage volume curves allows use of the information to size hotel/motels for facilities both larger and smaller than just those from which the data is derived. This is especially true for sizing to serve the guest room circuit loads that are proportional to occupancy. Remember, however, that the CV*dt* curves being presented here are for bathing-dominated hot-water circuits, and do not include laundry or food-service loads or larger common-area cleaning loads that would be associated with large meetings.

Figure 19 shows the non-dimensionalized CV*dt* curves for the main guest room hot water circuits for the travel and business hotels tested under RP-1544. The result shows that the "design hot-water use load profile curve" guest room circuit non-dimensionalized CV*dt* curves were very similar for both hotels over a time interval of less than 3 h. In both cases the peak hot-water uses over that time frame were driven by bathing. After the initial 3 h interval, hot-water use at the travel hotel is initially fairly high until about a 6 h time interval, and then falls off for the next 6 h. This reflects the fact that in the travel hotel room cleaning began in earnest as guests checked out (in the 6:00 to 9:00 am time frame in real time) and was mostly completed by early afternoon. Later increases in hot-water use reflect evening bathing.

In comparison, in the business hotel room cleaning proceeded at a slower pace after guest checkout, and baseload common area cleaning continued most of the afternoon and evening. These CV*dt* curves inherently contain the hot water load diversity information, allowing them to be directly used for system sizing purposes. Given the differences in the magnitude and timing of baseload/variable hot water use, it is important to use the CV*dt* curve appropriate to the type of hotel/motel being designed (e.g. with or without meeting rooms). Remember, the CV*dt* curves shown are for hot water circuits whose primary large loads are bathing. Differences in hot-water loads appear mostly after the morning peak hot-water use period is over. Do not use this curve when food service, laundry loads, or cleaning of large meeting spaces are to be served from the circuit; instead, see the RP-1544 final report and related technical papers.

Figures 20 and 21 show the non-dimensionalized needed heating rate versus non-dimensionalized cumulative volume curves for the travel and business hotels of the RP-1544 research. Recognize that the slope of the CV*dt* curve represents a flow rate. Applying needed temperature rise and properties of water using Equation (1), the needed heating rates are computed from either the average slope from the origin to the selected volume of interest (bottom-up or multi-pass heating) or the local slope at a selected volume (top-down or single-pass heating).

Remember, however, that the minimum acceptable heating rate is one that will heat the design 24 h hot water cumulative volume in 24 h (1440 min). That minimum needed heating rate is sometimes larger than the local slope of the CV*dt* curve, and should be substituted whenever that occurs. Additionally note that temperature and number of rooms terms cancel when non-dimensionalizing, so the non-dimensionalized curves are not functions of temperature or number or rooms or flow rates of fixtures. (i.e., the non-dimensionalized curves represent mostly time diversity of draws). Knowledge of the needed temperature rise, number of bathing events (related to number of rooms and peak occupancy) and fixture flow rates are needed during final computation steps when reintroducing dimensionalized results for sizing. Table 8 shows the data points of Figures 19, 20, and 21 for convenient use by readers when doing practice sizing calculations using the CV*dt* sizing approach.

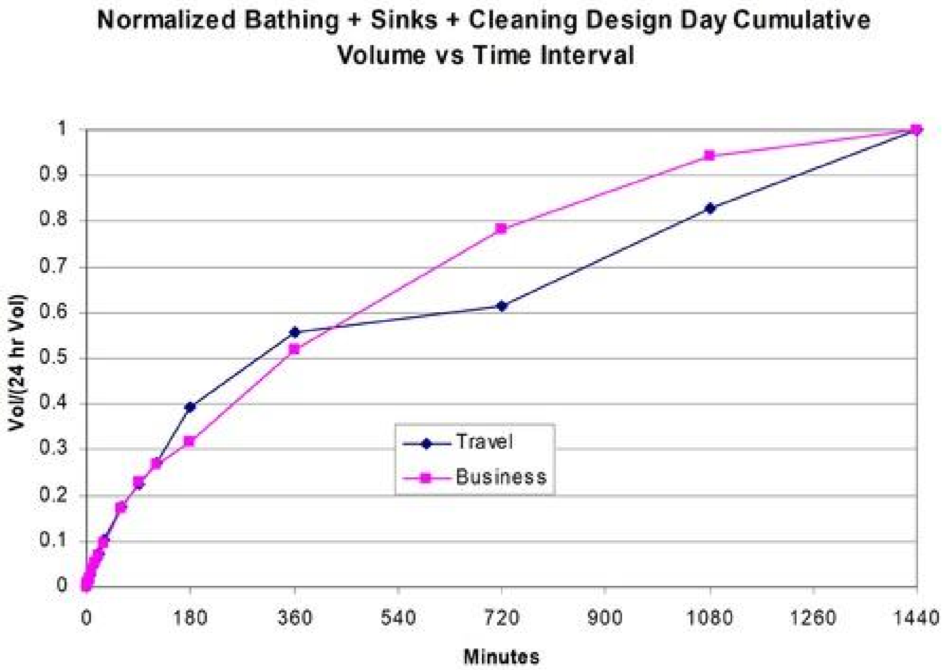

Figure 19. Nondimensionalized "Guest Room Circuit" Design Condition, Cumulative Volume versus Time Interval Plots, Field Test Hotels

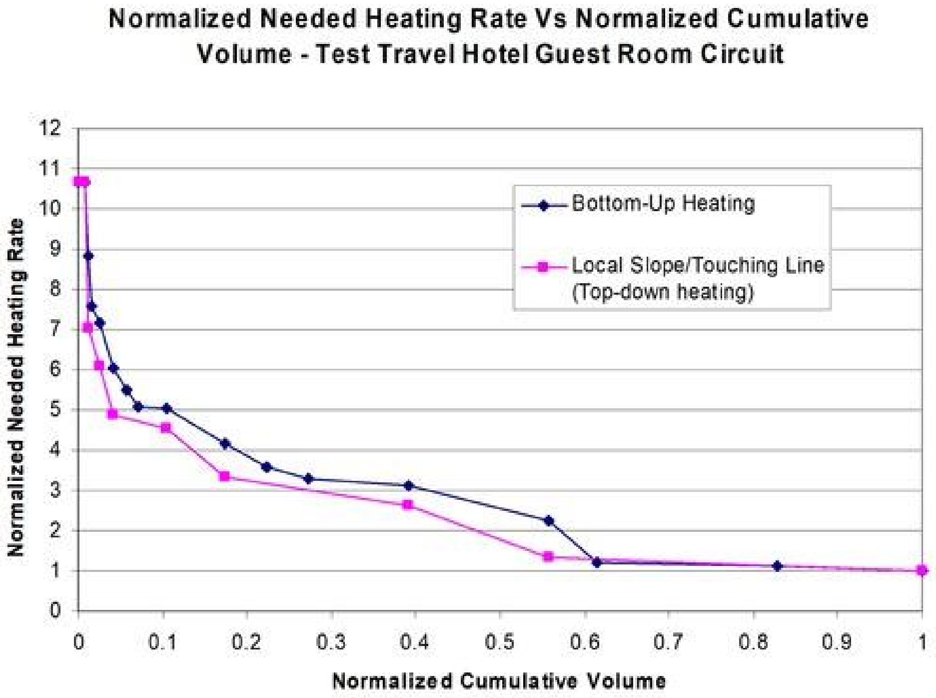

Figure 20. Non-Dimensionalized Needed Heating Rate versus Non-Dimensionalized Cumulative Volume, Test Travel Hotel Guest Room Circuit

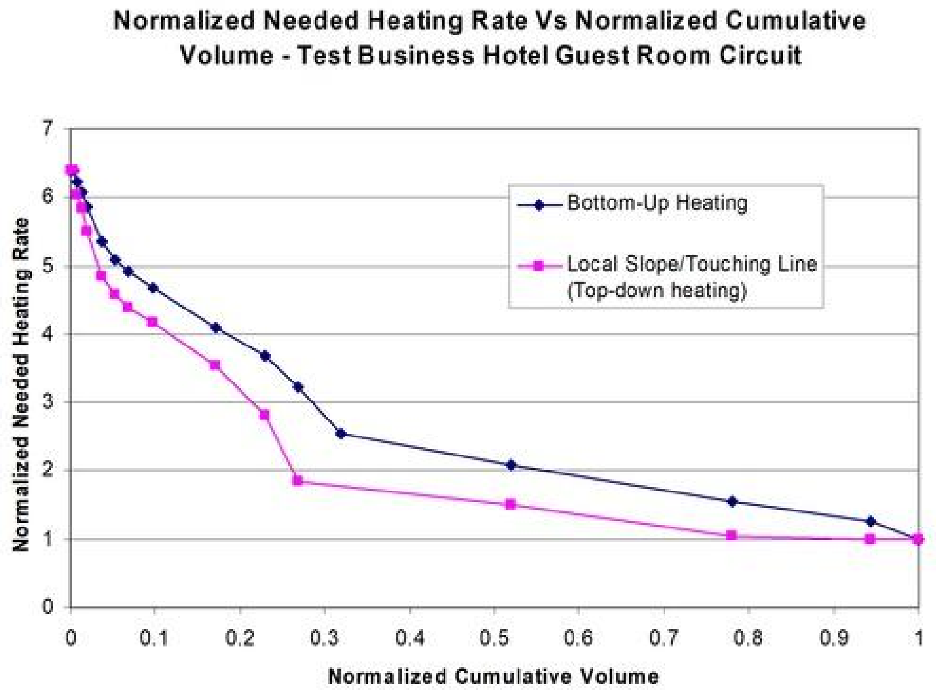

Figure 21. Non-Dimensionalized Needed Heating Rate versus Non-Dimensionalized Cumulative Volume, Test Business Hotel Guest Room Circuit

Sizing Examples

Example 1: Apartment Building. Evaluate the range of water-heating system heating-rate and storage volume combinations that can serve a 58-unit apartment building occupied by a mix of families, singles, and middle-income couples in which most adults work. The peak expected number of building occupants is 198, based on the assortment of apartment sizes in the building. Assume a water-heating system delivery temperature of 50°C, design entering cold-water temperature of 4°C, and heating device thermal efficiency of 80%.

Bottom-Up or Multi-Pass Heating.

Bottom-Up Heating Solution: The stated occupant demographics represent a medium load. Multiplying the volume per person versus time from the medium values in Table 7 by the number of occupants gives the cumulative amount needed at any point in time and the average flow rate (and hence heating rate) required through that time (representing bottom-up or multi-pass heating).

At 5 min, the peak design cumulative volume is (2.6 L/person) × (198 people) = 515 L. The average flow rate over 5 min is (515 L)/(5 min)/(60 s/min) = 1.7 L/s. The required heating rate is thus, from Equation (1) and dividing by the input efficiency,

$$q = (1.7 \text{ L/s})(1 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)} \\ \times (50 - 4°\text{C})/0.8 = 409 \text{ kW}$$

Assuming 70% of the storage tank volume can be extracted at a useful temperature (the other 30% being degraded by mixing in the tank), the required tank volume for this heating rate is

$$V = 515 \text{ L}/0.7 = 736 \text{ L}$$

Note that, because the heating rate divided by storage capacity (555 W/L) exceeds 300 W/L, this system is considered an instantaneous water heater.

At 60 min, 18.2 L/person)(198 people) = 3604 L. Average flow rate = (3604 L/60 min)/(60 s/min) = 1 L/s.

$$q = (1 \text{ L/s})(1 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)} \\ \times (50 - 4°\text{C})/0.8 = 240 \text{ kW}$$

$$V = 3604 \text{ L}/0.7 = 5149 \text{ L}$$

Doing these calculations at other volumes and times yields the combinations of heating rate and storage volume that can serve the load (Table 9).

Top-Down Heating.

The preceding bottom-up or multi-pass heating method calculates the needed heating rate by computing the average water flow rate from the beginning of the cumulative volume versus time interval curve. Using the average slope determined from the volume used at zero time interval and the volume used by any selected time interval represents the average heating rate needed to replenish the used volume by the selected time interval when heating storage from the bottom up (Hiller and Johnson 2017a). Alternatively, if top-down or single-pass heating is used, the water-heating device only needs to provide a heating rate computed from the local slope of the hot-water use curve, not the average slope. In other words for example, the flow over the first 5 min could have been provided entirely from storage without any heat input at all. The water heater only needs to heat in real time the amount of hot water needed over succeeding time periods. However, the needed heating rate can never be lower than that required to reheat the total 24 h hot water drawn by the end of the (24 h) design condition. Using the local slope of the CV*dt* curve at a selected time interval to determine needed heating rate as opposed to the average slope represents heating storage from the top down or otherwise near the outlet end of the heater (Hiller and Johnson 2017a). This is sometimes done, for example by using multiple water heaters with interlocked controls that force the water heater closest to the load to heat before the next furthest away water heater reheats. It is also sometimes achieved by using a variable-flow-rate pump, circulating water from an external heater into the top of a storage tank, by modulating the flow of the pump so that the temperature of water delivered to the outlet of storage (or directly to the load) is immediately hot enough to use. Top-down heating always requires at least slightly lower heating rates for a selected storage volume, or conversely at least slightly lower volumes for a selected heating rate than bottom-up heating.

Top-Down Heating Solution: The top-down heating sizing method uses the local slope of the cumulative volume hot-water use curve versus time interval to determine the necessary heating rate associated with each storage volume/time interval.

At 5 min, the peak design cumulative volume (Table 9) is 515 L. At 15 min, the peak design cumulative volume (Table 9) is 1267 L. The incremental flow rate (representing the local slope of the hot water use line) is hence (1267 – 515 L)/600 s =1.25 L/s. The needed top-down heating rate is thus computed as

$$Q = (1.25 \text{ L/s})(1 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)}] \\ (50°\text{C} - 4°\text{C})/0.8 = 303 \text{ kW}$$

Note that heating rate divided by storage capacity (411 W/L) exceeds 300 W/L, so the top-down heating system is still considered an instantaneous water heater.

From Table 9, the peak design cumulative volume at 120 min is 5999 L, and is 8237 L at 180 min. The incremental flow rate slope is thus ((8237 – 5999 L)/3600 s = 0.62 L/s. The heating rate needed when using 5999 L of storage is computed as

$$Q = (0.62 \text{ L/s})(1 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)}](50°\text{C} - 4°\text{C})/0.8 \\ = 151 \text{ kW}$$

From Table 9, the peak design cumulative volume at 180 min is 8237 L, and at 1440 min is 36 729 L. Consequently, the incremental flow rate slope is (36 729 – 8237 L)/75 600 s = 0.38 L/s. The heating rate needed when using 8237 L of storage is thus computed as

$$Q = (0.38\ \text{L/s})(1\ \text{kg/L})[4.1868\ \text{kJ/(kg·K)}](50°\text{C} - 4°\text{C})/0.8 = 91.5\ \text{kW}$$

It is important to recognize, however, when using the top-down heating rate sizing method, that storage must eventually be reheated. The minimum heating rate used should therefore not be less than that computed using the 24 h average flow rate.

Doing these calculations at other volumes and times yields the top-down heating combinations of heating rate and storage volume that can serve the load, as shown in Table 10.

Table 8 Data for Figures 19, 20, and 21

	Non-Dimensionalized Storage Volume		Travel Hotel Non-Dimensionalized Needed Heating Rates		Business Hotel Non-Dimensionalized Needed Heating Rates	
Time inter-val (min)	Travel Hotel	Business Hotel	From Local Slope of Touching Line (top-down or single-pass heating)	From Slope to Origin (bottom-up or multi-pass heating)	From Local Slope of Touching Line (top-down or single-pass heating)	From Slope to Origin (bottom-up or multi-pass heating)
0	0	0	10.65	10.65	6.40	6.40
1	0.0074	0.0044	10.65	10.65	6.40	6.40
2	0.0123	0.0086	7.04	8.84	6.04	6.22
3	0.0158	0.0127		7.58	5.83	6.09
5	0.0249	0.0203	6.07	7.18	5.51	5.86
10	0.0419	0.0371	4.89	6.03	4.83	5.34
15	0.0574	0.0530		5.51	4.59	5.09
20	0.0707	0.0683		5.09	4.39	4.92
30	0.1047	0.0972	4.52	5.03	4.16	4.66
60	0.1744	0.1709	3.34	4.19	3.54	4.10
90	0.2237	0.2294		3.58	2.81	3.67
120	0.2726	0.2676		3.27	1.83	3.21
180	0.3918	0.3183	2.61	3.13		2.55
360	0.5583	0.5194	1.33	2.23	1.51	2.08
720	0.6137	0.7807		1.23	1.04	1.56
1080	0.8286	0.9442		1.10	1	1.26
1440	1	1	1	1	1	1

Table 9 Example 1, Bottom-Up Heating: Heating Rate and Storage Volume Options

Time, min	Litres per Person	Total Litres for 198 People	Average Litres per Second	Heating Rate, kW	Storage Volume, L
5	2.6	515	1.7	409	736
15	6.4	1 267	1.4	337	1810
30	11.0	2 178	1.2	288	3111
60	18.2	3 604	1.0	240	5149
120	30.3	5 999	0.83	200	8570
180	41.6	8 237	0.76	183	11 767
1440	185.5	36 729	0.43	103	52 470

Note that Example 2 is only available in I-P units, but is included here for illustrative purposes in the SI volume. ASHRAE apologizes for the inconvenience, but felt that the demonstration's importance meant it should be offered to everyone, regardless of units.

Example 2: Hotel. Evaluate the range of water-heating system heating-rate and storage volume combinations that can serve the main guest room circuit of a 100 room hotel/motel having no meeting rooms or food service and sheet and towel washing done off site. Assume a water-heating system delivery temperature of 125°F, design entering cold-water temperature of 50°F, a heating device thermal efficiency of 80% and a 70% useful storage volume. Assume hotel common area is 8000 ft^2. Assume guest room circuit baseload/variable hot-water use is proportional to common area size, at 0.056

gal/ft^2·day.

Solution Using the Modern CV*dt* method: This example hotel/motel is similar to the test travel hotel so values for that system will be used when determining sizing. The first step is to estimate the design condition 24 h hot-water volume used. Remembering that number of guests/day = number of bathing events/day and the average bathing event is a shower using 12 gal of hot water,

$$V_{24} = (\text{number of guest rooms})(\text{guests/room})(12\ \text{gal/shower/guest}) + V_{\text{base/variable}}$$

$$V_{\text{base/variable}} = (0.056\ \text{gal/ft}^2\cdot\text{day})(8000\ \text{ft}^2) = 448\ \text{gal/day}$$

$$V_{24} = (100\ \text{guest rooms})(2.8\ \text{showers/room})(12\ \text{gal/shower}) = 3360\ \text{gal/day} + 448\ \text{gal/day} = 3808\ \text{gal/day}$$

Special note: Baseload/variable hot-water use is not necessarily proportional to hotel common area; until better information on what makes that type of hot-water use be what it is becomes available, values are simply assumed. However, given the example hotel description (no meeting rooms, no food service, no laundry), in this case the baseload/variable portion of hot-water use will be fairly small compared to bathing hot-water use.

The second step is to determine the estimated minimum needed heating rate under the design condition curve:

$$\text{Min. needed heating output rate} = (3808\ \text{gal/24 h})(8.3\ \text{lb/gal}) \times (1\ \text{Btu/lb °F})(125 - 50°\text{F}) = 98{,}770\ \text{Btu/h}$$

Note that this is the minimum needed water heating output rate, but water heaters are specified based on heat input rate, so needed heating rates must be divided by assumed heat input efficiency to determine needed heating input rate. Moreover, in a real system design, the heating rate must be large enough to also make up for distribution piping and storage heat losses, so those must also be computed and added to the total needed heating rate (not done in this simplified example).

Applying the computed minimum needed heat output rate and maximum daily hot-water use volume to the data in Table 8 and Figure 20 gives the results shown in Table 11 and Figure 22. The hot-water production capability of an instantaneous water heater with 4000 Btu/h·gal of storage is also shown in Figure 22 for reference.

Note that large reductions of needed storage volume can be gained by supplying heating rates only slightly above the minimum heating rate to just supply the design condition total hot water load in 24 h. This is generally possible because most hotels do not use much hot water at night. There are also several advantageous sizing points that should be considered, as indicated by sharp bends in the needed heating rate versus storage volume curves. For example, using the bottom-up heating curves to be conservative, supplying a storage volume of 269 gal gets the system through the morning peak bathing period while using a heating rate of 503,000 Btu/h, a value that is substantially lower than would be needed by a tankless or instantaneous water heater. Another significantly beneficial possible combination of heating rate plus storage comes in supplying 1038 gal of storage which gets the system through the room cleaning operations plus the peak bathing periods, while only requiring 323,000 Btu/h of heating rate, compared to many times that if a tankless water heater is used.

Actual needed heat input rates and storage volumes for the two sizing options described above would be

$$269\ \text{gal}/0.7 = 384\ \text{gal of storage} + 503{,}000\ \text{Btu/h}/(0.8) = 628{,}750\ \text{Btu/h}$$

$$1038\ \text{gal}/(0.7) = 1483\ \text{gal of storage} + 323{,}000\ \text{Btu/h}/(0.8) = 403{,}750\ \text{Btu/h}$$

Note that many factors are involved in selecting a water heating system; selecting a workable heating rate and storage volume combination is just the beginning. Cost is an important factor, and some technologies such as solar and heat pump water heaters favor having lower heating rates and larger amounts of storage than some other technologies. The need for some level of redundancy is also important and impacts for example using multiple smaller systems versus fewer larger ones; it is one reason hotel water heating systems have multiple heaters. Note too that since the cumulative volume versus time interval method uses worst-case order of occurrence hot water use information (Hiller and Johnson 2015, 2016a, 2016b, 2016c, 2017a, 2017b), adding additional heating capacity or storage volume as factors of safety is unnecessary: the cumulative volume versus time interval method is already a conservative sizing method. However, designers can still add some safety factor if they choose.

Solution Using the Werden & Spielvogel Motel Curves of Figure 26. The Werden and Spielvogel (W&S; 1969a, 1968b) motel sizing curves of Figure 26 can also be used to size the 100 room hotel/motel. Examination of the original W&S test data shows that the 100 room curve comes from data from only one test site having 113 rooms, with data collected for a total of 65 days. That data showed peak room occupancy during the data collection period was around 0.95 guests/room (as compared to the 2.8 guests/room found in the much newer RP-1544 hotel field test data). Moreover, the W&S plots came from 1 h data and hence the plots lacked small enough data collection intervals with which to size instantaneous and semi-instantaneous water heaters using the data. Figure 23 shows the Figure 26 motel plots after they have been non-dimensionalized and how they compare to the non-dimensionalized data from the RP-1544 hotel field test. The W&S plots all represent bottom-up heating. The non-dimensionalized Figure 26 plots have also had data points removed that would have had to have come from data collected over periods of less than 60 min in order to be valid data.

Given that the W&S data had a peak room occupancy of 0.95 guests/room on peak use days. compared to the more recent RP-1544 hotel field test data showing design condition room occupancies of 2.5 to 2.8 guests/room, decisions must be made. Simply using the plots of Figure 26 to size the system means that the system will be sized assuming maximum room occupancy of 0.95 guests/room and hence a system thus sized will be smaller than if 2.5 to 2.8 guests per room are assumed. There are two methods to correct for the peak design room occupancy discrepancy. One is to simply multiply the heating rate values from the 100 room plot of Figure 26 times the ratio of newer to older design condition occupancy (i.e., by multiplying heating rate results by 2.8/0.95 = 2.95), plus some minimum extra heating rate to provide the baseload 448 gal of hot water in 24 h since baseload hot-water use is not included in the Figure 26 plots. The other method is to use the non-dimensionalized 100 room curve given in Figure 23 (or the non-dimensionalized test travel hotel curve; results will be similar at least at lower assumed volumes) and determine needed heating rates versus storage volumes the same way as when using the more modern CV*dt* curves.

Using the 100 room plot of Figure 26 for motels from the W&S work, the maximum useful storage volume is (16 gal/room)(100 rooms) = 1600 gal (6056 L). Dividing that by a useful storage volume of 70% yields 1600/(0.7) = 2286 gal. The minimum needed heating rate is (1gal/h·room)(100 rooms) = 100 gal/h, thus minimum needed heating rate is (100 gal/h)(8.3 lb/gal)(1 Btu/lb F)(125 – 50 F) = 62,250 Btu/h, to which must be added the extra minimum baseload hot water use heating rate of (448 gal/24 hr)(8.3 lb/gal)(1Btu/lb F)(125-50 F) = 11,620 Btu/h, resulting in the minimum total needed heating rate = 62,250 +11,620 = 73,870 Btu/h. And accounting for heater input efficiency needed heating rate = (73,870 Btu/h)/(0.8) =92,337 Btu/h. Correcting for the design condition room occupancy discrepancy gives (62,250 Btu/h)(2.95) = 183,638; thus total minimum needed heating rate is 183,638 + 11,620 = 195,258 Btu/h (57 kW) and (195,258)/0.8) = 244,072 Btu/h (72 kW).

Using the smallest volume shown for the 100 room hotel in Figure 26 (after removing data points that could not have come from 1 h data and were hence probably extrapolated), required storage volume is (3 gal/room)(100 rooms) = 300 gal, and dividing by storage volumetric efficiency yields (300 gal)/(0.7) = 429 gal (1622 L). The corresponding needed heating rate = (2.7 gal/h/room)(100 rooms) = 270 gal/h (1022 L/h), such that needed heating rate is = (270 gal/h)(8.3 lb/gal)(1 Btu/lb F)(125 – 50°F) = 168,075 Btu/h plus the 11,620 Btu/h minimum baseload heating rate = 179,695 Btu/h, which divided by heat input efficiency becomes (179,695 Btu/h/h)/(0.8) = 224,619 Btu/h. Correcting for the design condition room occupancy discrepancy gives (168,075 Btu/h)(2.95) = 495,821 Btu/h + 11,620 Btu/h = 507,441 Btu/h and (507,441 Btu/h)/(0.8) = 634,301 Btu/h.

Doing these calculations for other points on the 100 room plot from Figure 26 yields the combinations of needed heating rate versus storage volume shown in Table 12.

Using the non-dimensionalized 100 room data from Figure 23, and the same computation techniques as shown above when using the non-dimensionalized modern CV*dt* curves from RP-1544, gives the needed heating rates versus storage volumes shown in Table 12. Figure 24 compares the Example 2 needed heating rates versus storage volumes from all the solution methods demonstrated. Assuming 0.95 guests per room under the design condition results in a fairly small system. Using the adjustment techniques to represent more realistic design condition room occupancy (2.8 guest/room in this case) puts the predicted needed heating rates versus storage volumes in closer agreement with results expected based on the much more modern RP-1544 data. Even then, however, there are limitations on how well the adjustment techniques used work because trying to adjust curves from one guest/room to 2.8 guests/room does not represent evening bathing very well. Little evening bathing occurs when occupancy is low. That is why the adjusted curves still demonstrate lower needed heating rates in the mid-volume range compared to the modern RP-1544 data.

Table 10 Example 1, Top-Down Heating Method: Heating Rate and Storage Volume Options

Time, min	Litres per Person	Total Litres for 198 People	Local Slope of Incremental Litres per Minute	Heating Rate, kW	Storage Volume, L
5	2.6	139515	19.81.2	997,920303	198736
15	6.4	3371267	15.80.97	796,320233	4811810
30	11.0	5742178	12.50.77	630,000191	8203111
60	18.2	9503604	10.60.65	534,240162	1,3585149
120	30.3	15845999	9.90.61	498,960151	2,2638570
180	41.6	21788237	5.970.37	339,570103*	3,11111 767
1440	185.5	970236 729	70.43	339,570103	13,86052 470

* Heating rate should not be lower than that needed to satisfy load on a 24 h basis.

Table 11 Example Travel Hotel Guest Room Circuit Needed Heating Rates versus Storage Volume

Time Interval, min.	Cumulative Volume, gal	Needed Heating Rate, Btu/h (top-down heating)	Needed Heating Rate, Btu/h (bottom-up heating)
0	0	1,051,837	1,051,837
1	28	1,051,837	1,051,837
2	47	695,255	873,546
3	60	663,448	748,417
5	94	599,834	709,319
10	160	482,510	595,914
15	219	473,591	544,677
20	269	464,672	502,535
30	399	446,835	496,528
60	664	330,359	413,444
90	851	312,181	353,553
120	1038	294,002	323,087
180	1492	257,645	309,578
360	2126	131,543	220,561
720	2337	120,619	121,226
1080	3156	109,694	109,120
1440	3808	98,770	98,770

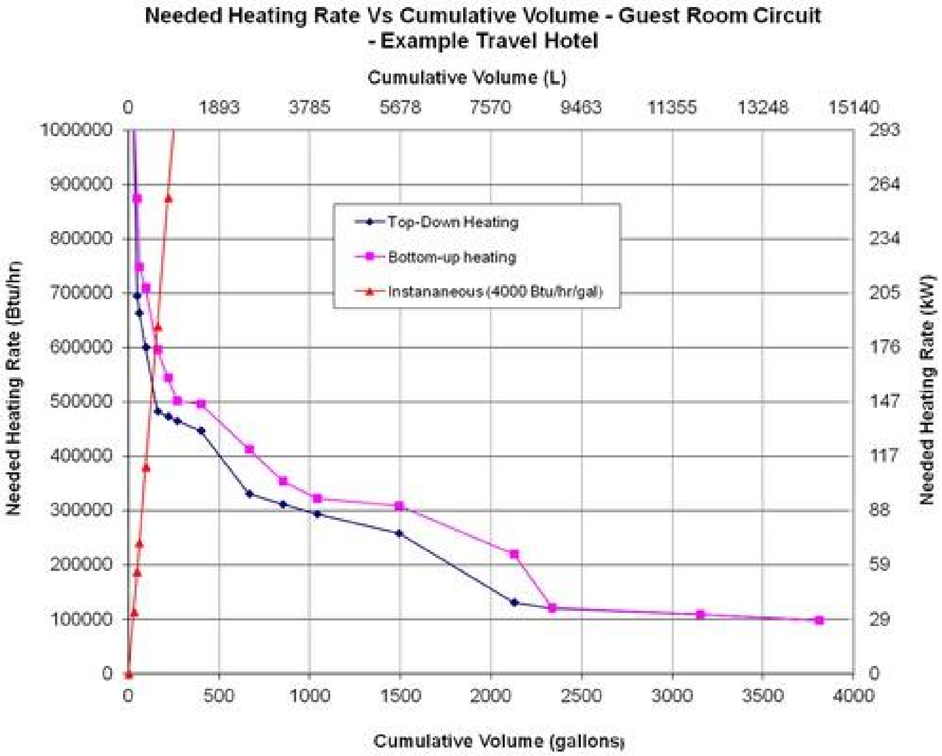

Figure 22. Example Travel Hotel Acceptable Heating Rate versus Storage Volume Combinations Guest room circuit only using CV*dt* method.

Table 12 Example 2, Hotel/Motel Sizing Using W&S Motel Plots of Figure 26 with Baseline/Variable Hot-Water Use

Storage Volume, gal	Bottom-up Needed Heating Rate, Btu/h 0.95 guests/room	Bottom-up Needed Heating Rate Btu/h 2.8 guests/room	Storage Volume, gal from non-dimensionalized analysis	Bottom-up Needed Heating Rate, Btu/h 2.8 guests/room from non-dimensionalized analysis
300	179,695	507,441	714	266,679
400	164,132	461,532	952	241,986

500	148,570	415,623	1190	217,294
600	126,782	351,349	1428	182,724
700	114,332	314,622	1666	162,970
800	98,770	268,713	1904	138,278
900	89,432	241,167	2142	123,462
1000	83,207	222,803	2380	113,585
1100	76,982	204,439	2618	103,708
1200	73,870	195,258	2856	98,770
1600	73,870	195,258	3808	98,770

Note: Divide volumes by 0.7 to account for percent of storage that is useful, and heating rates by 0.8 to account for heat input efficiency.
W&S: Werden and Spielvogel (1969a, 1969b).

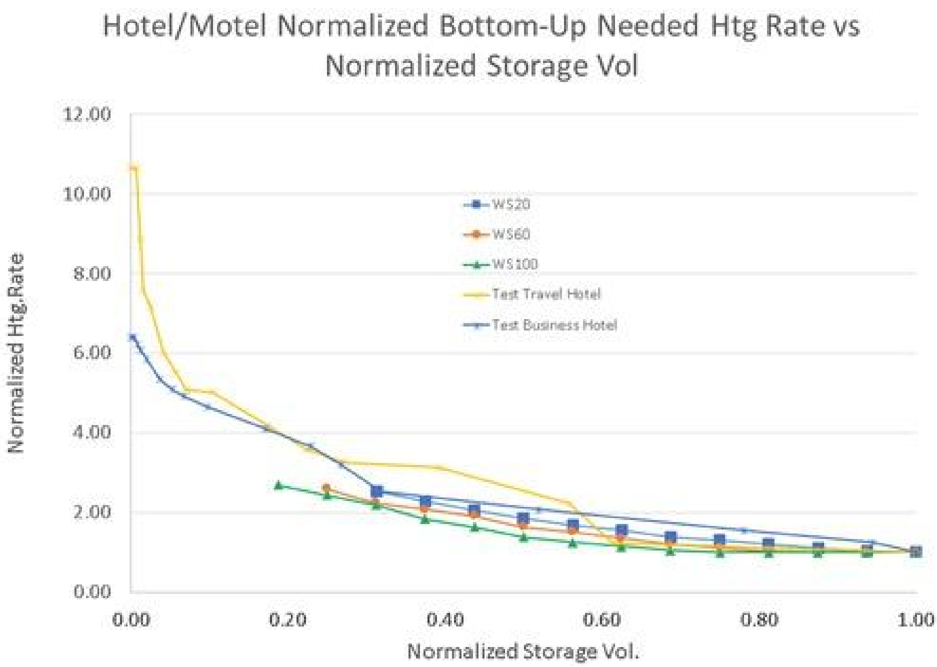

Figure 23. Comparison of W&S Motel versus Test Travel/Business Hotel Non-dimensionalized heating rate versus storage volume

There are several techniques to size water-heating systems using the more limited draw profile information in older data. Figures 25 to 32 show relationships between recovery and storage capacity for various building categories. Any combination of storage and recovery rate that falls on the proper curve satisfies building requirements. Using the minimum recovery rate and maximum storage capacity on the curves yields the smallest hot-water capacity able to satisfy the building requirement. The higher the recovery rate, the greater the 24 h heating capacity and the smaller the storage capacity required. Note that the data in Figures 25 to 32 predate modern low-flow fixtures and appliances.

These curves can be used to select recovery and storage requirements to accommodate water heaters that have fixed storage or recovery rates. Where hot-water demands are not coincident with peak electric, steam, or gas demands, greater heater inputs can be selected if they do not create additional energy system demands, and the corresponding storage tank size can be selected from the curves.

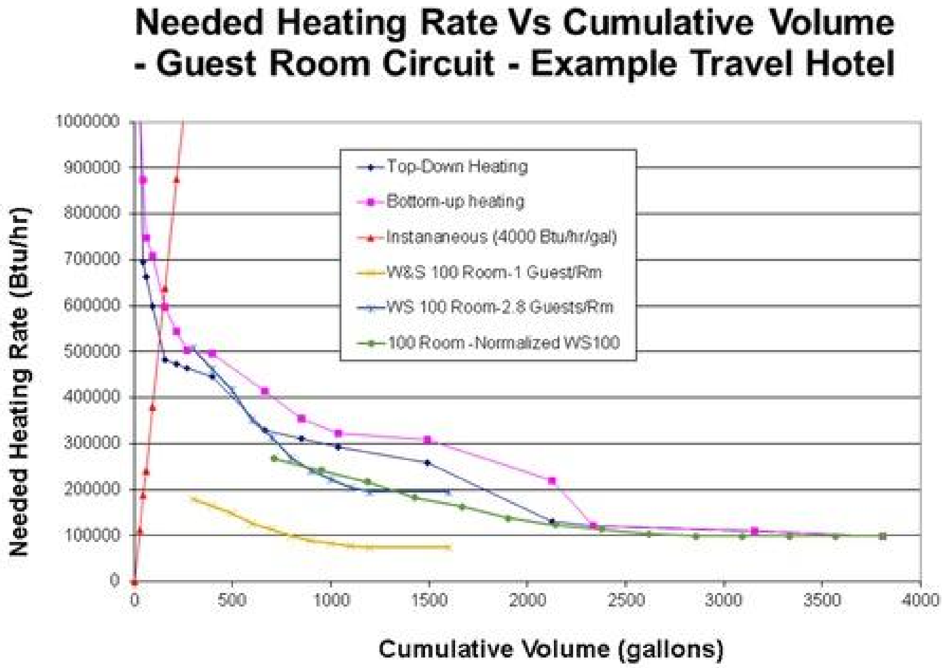

Figure 24. Example 2 Hotel/Motel Water Heating System Sizing Comparisons

Ratings of gas-fired water-heating equipment are based on sea-level operation and apply up to 600 m. For operation above 600 m, and in the absence of specific recommendations from the local authority, equipment ratings should be reduced by 4% for each 300 m above sea level before selecting appropriately sized equipment.

Recovery rates in Figures 16 to 23 represent the actual hot water required without considering system heat losses. Heat losses from storage tanks and recirculating hot-water piping should be calculated and added to the recovery rates shown. Storage tanks and hot-water piping must be insulated.

The storage capacities shown are net usable requirements. Assuming that 60 to 80% of the hot water in a storage tank is usable, the actual storage tank size should be increased by 25 to 66% to compensate for unusable hot water.

Figure 24 shows hourly flow profiles for a sample building in each category, so that readers may better understand the nature of energy withdrawal rate profiles that may need to be met in such applications. These buildings were selected from actual metered tests, but are not necessarily typical of all buildings in that category. Figure 24 should not be used for sizing water heaters, because a design load profile for a real building may vary substantially from these limited test cases.

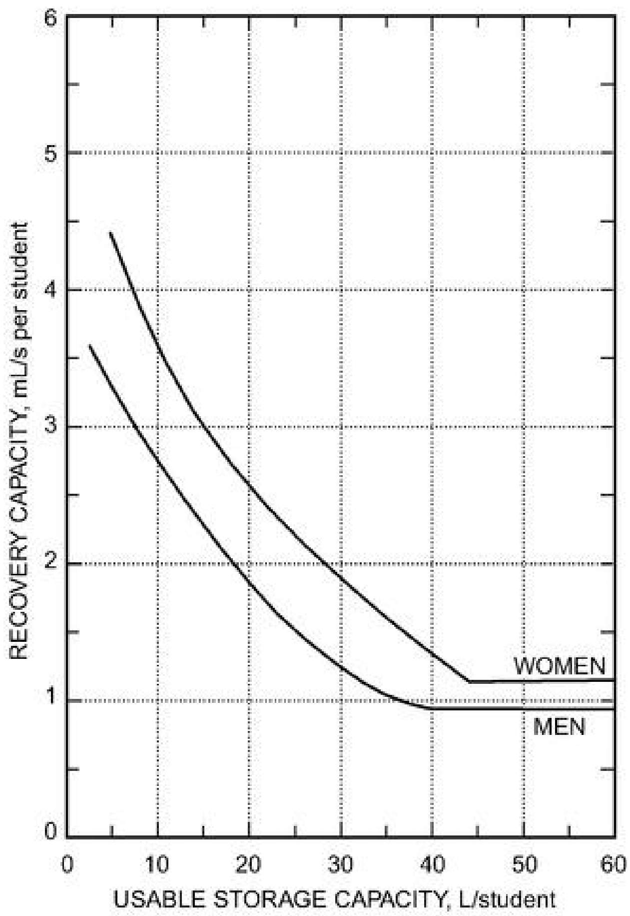

Figure 25. Dormitories

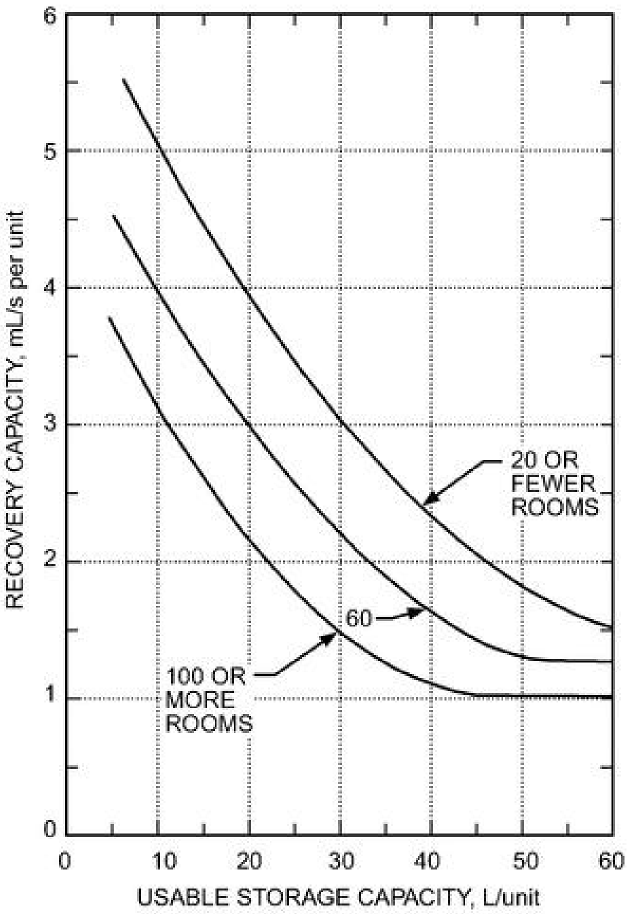

Figure 26. Motels

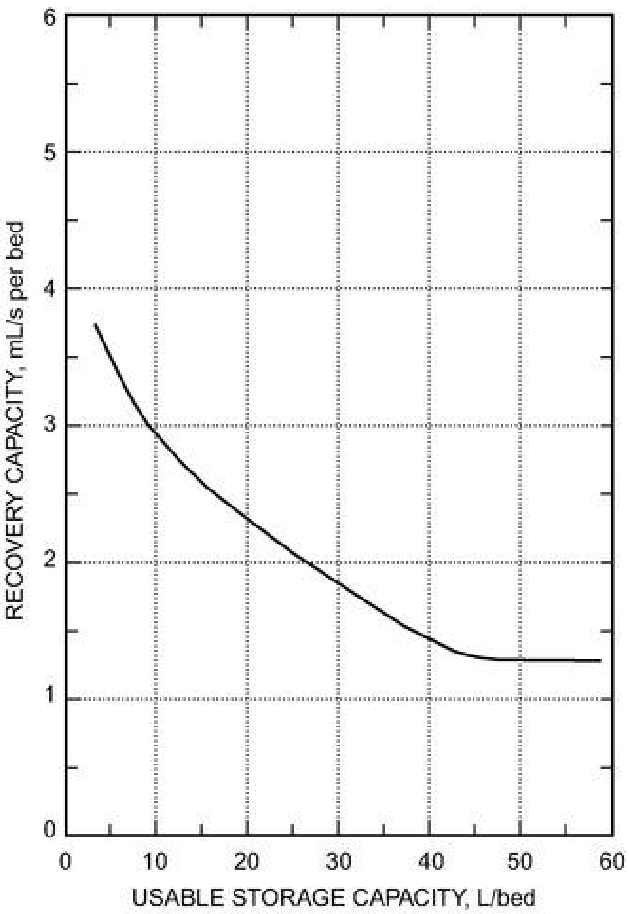

Figure 27. Nursing Homes

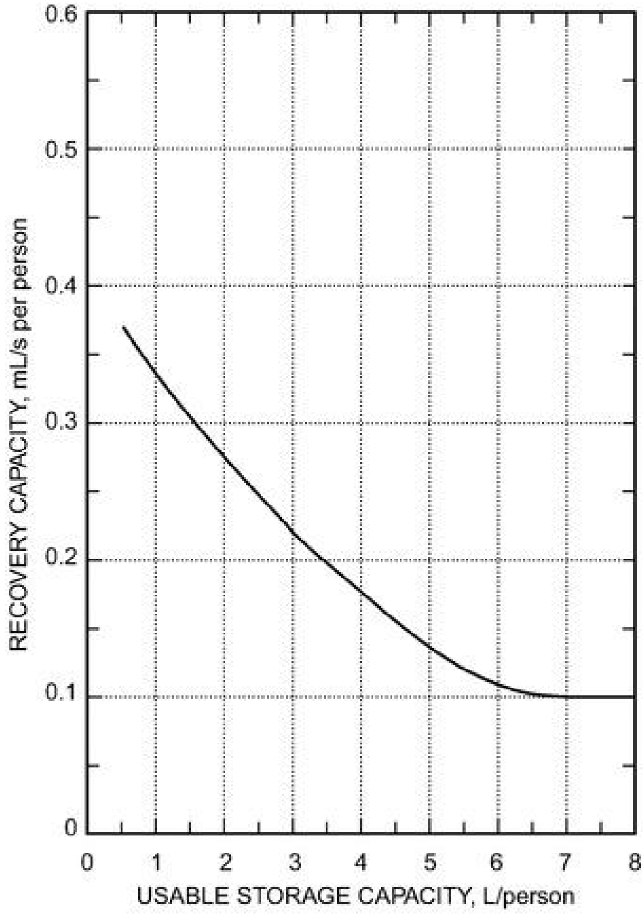

Figure 28. Office Buildings

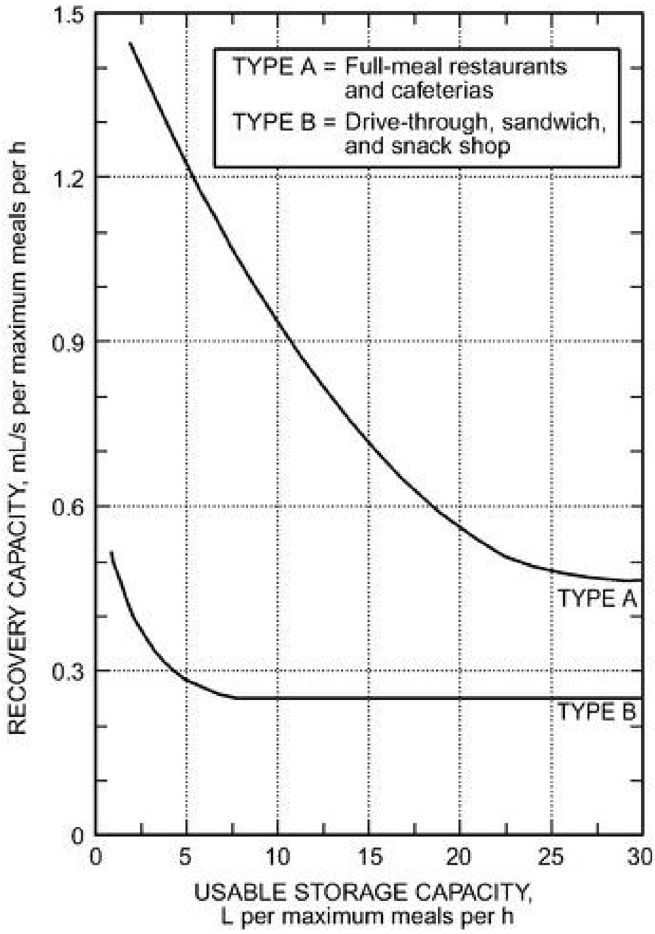

Figure 29. Food Service

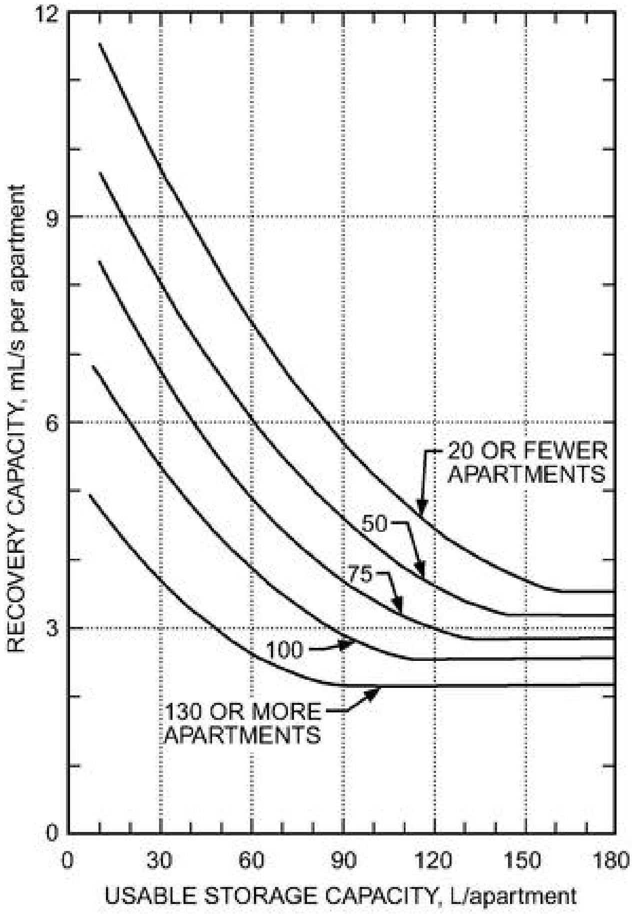

Figure 30. Apartments

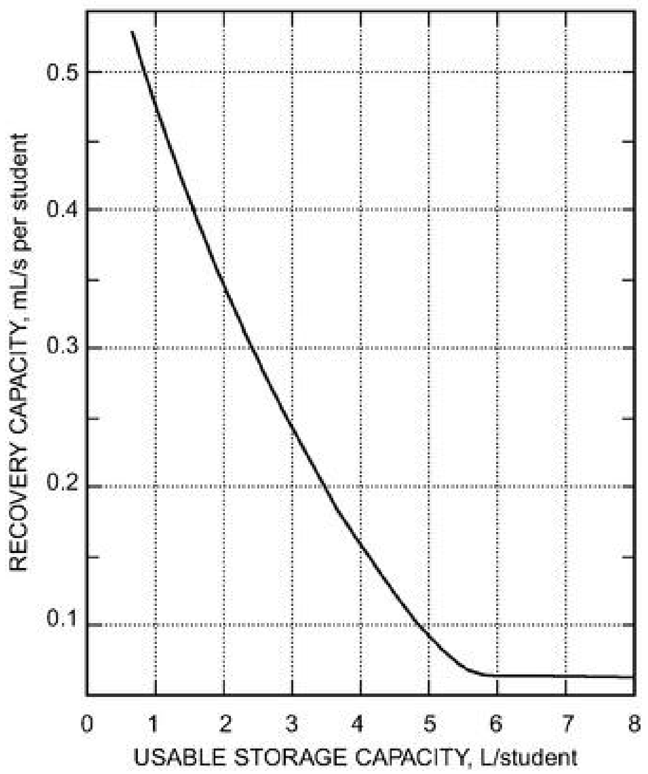

Figure 31. Elementary Schools

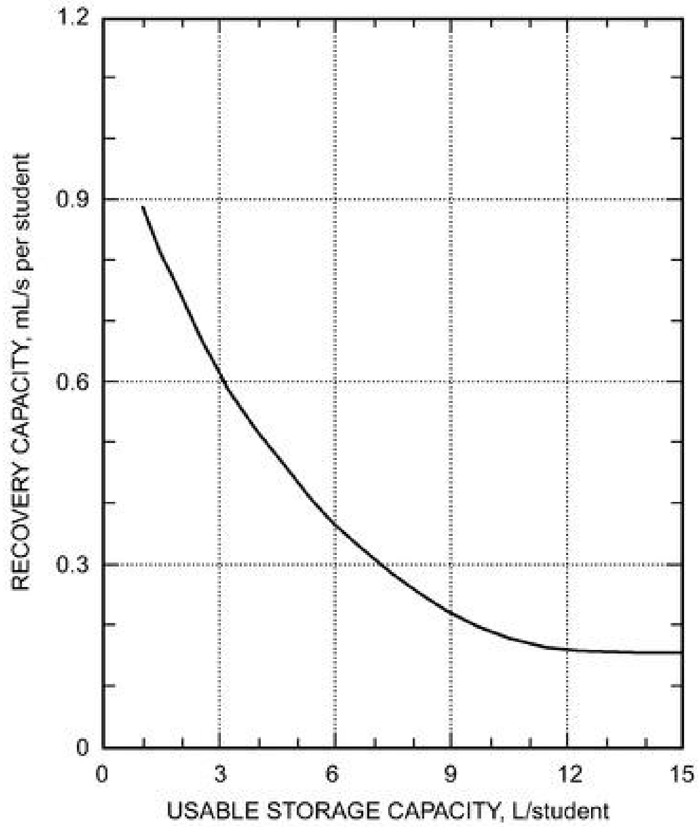

Figure 32. High Schools

Example 3. Determine the required water heater size for a 300-student women's dormitory for the following criteria:

a. Storage with minimum recovery rate

b. Storage with recovery rate of 2.6 mL/s per student

c. With the additional requirement for a cafeteria to serve a maximum of 300 meals per hour for minimum recovery rate, combined with item *a*; and for a recovery rate of 1.9 mL/s per maximum meals per hour, combined with item *b.*

Solution:

a. The minimum recovery rate from Figure 25 for women's dormitories is 1.1 mL/s per student, or 330 mL/s total. At this rate, storage required is 45 L per student or 13.5 m^3 total. On a 70% net usable basis, the necessary tank size is 13.5/0.7 = 19.3 m^3.

b. The same curve shows 20 L storage per student at 2.6 mL/s recovery, or 300 × 19 = 5700 L storage with recovery of 300 × 2.6 = 780 mL/s. The tank size is 5700/0.7 = 8140 L.

c. Requirements for a cafeteria can be determined from Figure 29 and added to those for the dormitory. For the case of minimum recovery rate, the cafeteria (Type A) requires 300 × 0.47 = 140 mL/s recovery rate and 300 × 26.5/0.7 = 11.4 m^3 of additional storage. The entire building then requires 330 + 140 = 470 mL/s recovery and 19.3 + 11.4 = 30.7 m^3 of storage.

With 1.0 mL/s recovery at the maximum hourly meal output, the recovery required is 300 mL/s, with 300 × 7.5/0.7 = 3260 mL/s of additional storage. Combining this with item *b,* the entire building requires 780 + 300 = 1080 mL/s recovery and 8140 + 3260 = 11 400 L = 11.4 m^3 of storage.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset system heat losses.

Example 4. Determine the water-heater size and monthly hot-water consumption for an office building to be occupied by 300 people under the following conditions:

a. Storage with minimum recovery rate

b. Storage with 3.8 L per person storage

c. Additional minimum recovery rate requirement for a luncheonette open 5 days a week, serving a maximum of 100 meals per hour and an average of 200 meals per day

d. Monthly hot-water consumption

Solution:

a. With minimum recovery rate of 0.1 mL/s per person from Figure 28, 30 mL/s recovery is required; storage is 6 L per person, or 300 × 6 = 1800 L. If 70% of the hot water is usable, the tank size is 1800/0.7 = 270 L.

b. The curve also shows 3.8 L storage per person at 0.18 mL/s per person recovery, or 300 × 0.18

= 54 mL/s. The tank size is 300 × 3.8/0.7 = 1630 L.

c. Hot-water requirements for a luncheonette (Type B) are in Figure 29. With a minimum recovery capacity of 0.26 mL/s per maximum meals per hour, 100 meals per hour requires 26 mL/s recovery, and the storage is 7.6 L per maximum meals per hour, or 100 × 7.6/0.7 = 1090 L storage. The combined requirements with item *a* are then 56 mL/s recovery and 3660 L storage.

Combined with item *b,* the requirement is 80 mL/s recovery and 2720 L storage.

d. Average day values are found in Table 6. The office building consumes an average of 3.8 L per person per day × 30 days per month × 300 people = 34.2 m^3 per month and the luncheonette will consume 2.6 L per meal × 200 meals per day × 22 days per month = 11.4 m^3 per month, for a total of 45.6 m^3 per month.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat losses.

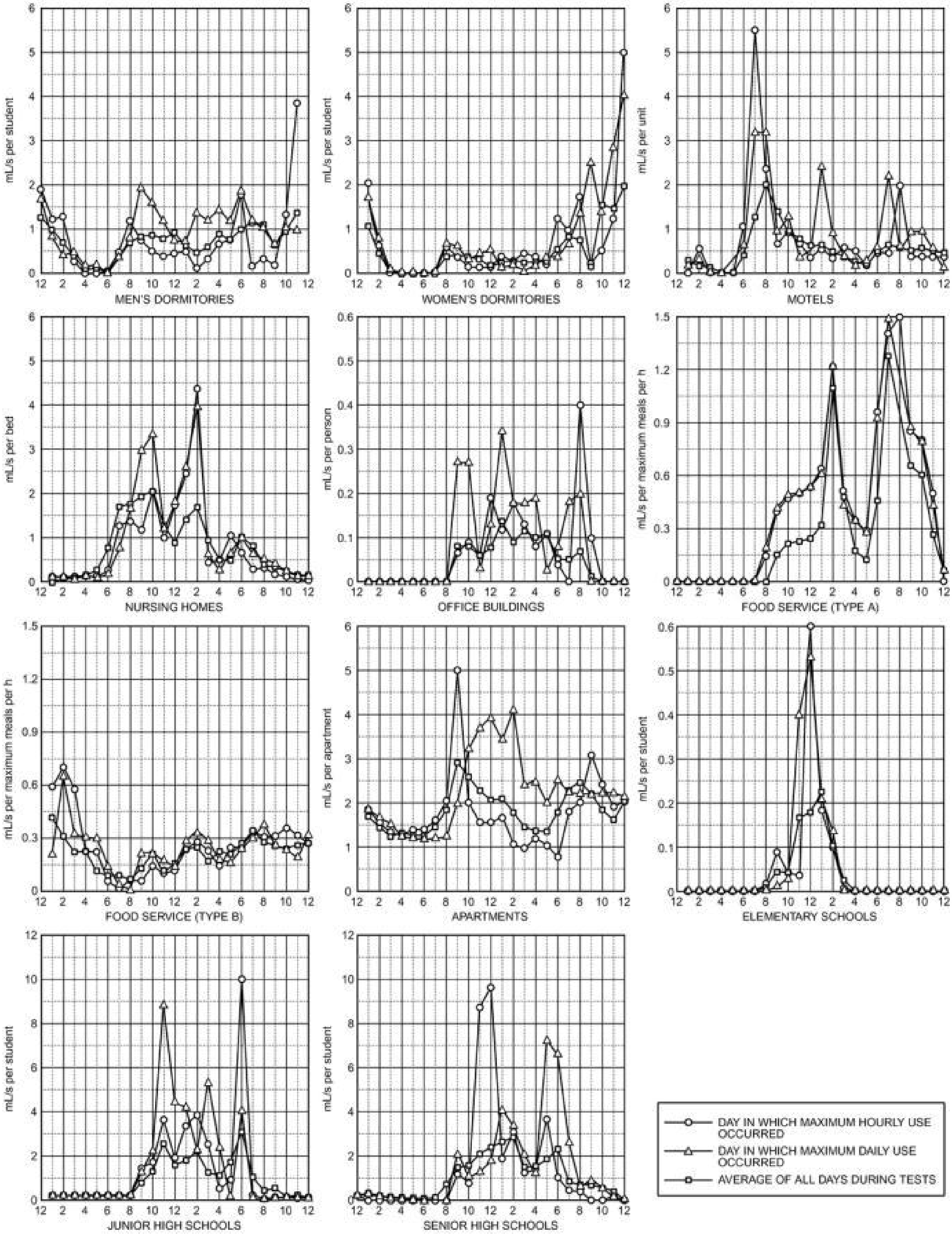

Figure 33. Hourly Flow Profiles for Various Building Types

Example 5. Determine the water heater size for a 200-unit apartment house under the following conditions:

a. Storage with minimum recovery rate

b. Storage with 4.2 mL/s per apartment recovery rate

c. Storage for each of two 100-unit wings

1. Minimum recovery rate

2. Recovery rate of 4.2 mL/s per apartment

Solution:

a. The minimum recovery rate, from Figure 30, for apartment buildings with 200 apartments is 2.2 mL/s per apartment, or a total of 440 mL/s. The storage required is 90 L per apartment, or 18 m^3. If 70% of this hot water is usable, the necessary tank size is 18/0.7 = 25.7 m^3.

b. The same curve shows 19 L storage per apartment at a recovery rate of 4.1 mL/s per apartment, or 200 × 4.2 = 840 mL/s. The tank size is 200 × 19/0.7 = 5.43 m^3.

c. Solution for a 200-unit apartment house having two wings, each with its own hot-water system.

1. With minimum recovery rate of 2.6 mL/s per apartment (see Figure 30), a 260 mL/s recovery is required, and the necessary storage is 106 L per apartment, or 100 × 106 = 10.6 m^3. The required tank size is 10.6/0.7 = 15.2 m^3 for each wing.

2. The curve shows that, for a recovery rate of 4.2 mL/s per apartment, storage is 50 L per apartment, or 100 × 50 = 5 m^3, with recovery of 100 × 4.2 = 420 mL/s. The necessary tank size is 5/0.7 = 7.2 m^3 in

a. Storage with minimum recovery rate

b. each wing.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat loss.

Table 13 HotWater Demand per Fixture for Various Types of Buildings (Litres of water per hour per fixture, calculated at a final temperature of 60°C)

		Apartment House	Club	Gymnasium	Hospital	Hotel	Industrial Plant	Office Building	Private Residence	School	YMCA
1.	Basin, private lavatory	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
2.	Basin, public lavatory	15	23	30	23	30	45.5	23	—	57	30
3.	Bathtub[c]	76	76	114	76	76	—	—	76	—	114
4.	Dishwasher[a]	57	190-570	—	190-570	190-760	76-380	—	57	76-380	76-380
5.	Foot basin	11	11	46	11	11	46	—	11	11	46
6.	Kitchen sink	38	76	—	76	114	76	76	38	76	76
7.	Laundry, stationary tub	76	106	—	106	106	—	—	76	—	106
8.	Pantry sink	19	38	—	38	38	—	38	19	38	38
9.	Shower	114	568	850	284	284	850	114	114	850	850
10.	Service sink	76	76	—	76	114	76	76	57	76	76
11.	Hydrotherapeutic shower				1520						
12.	Hubbard bath				2270						
13.	Leg bath				380						
14.	Arm bath				130						
15.	Sitz bath				114						
16.	Continuous-flow bath				625						
17.	Circular wash sink				76	76	114	76		114	
18.	Semicircular wash sink				38	38	57	38		57	
19.	DEMAND FACTOR	0.30	0.30	0.40	0.25	0.25	0.40	0.30	0.30	0.40	0.40
20.	STORAGE CAPACITY FACTOR[b]	1.25	0.90	1.00	0.60	0.80	1.00	2.00	0.70	1.00	1.00

Note: Data sources predate low-flow fixtures and appliances.

[a] Dishwasher requirements should be taken from this table or from manufacturers' data for model to be used, if known.

[b] Ratio of storage tank capacity to probable maximum demand/h. Storage capacity may be reduced where unlimited supply of steam is available from central street steam system or large boiler plant.

[c] Whirlpool baths require specific consideration based on capacity. They are not included in the bathtub category.

Example 6. Determine the water-heater size and monthly hot-water consumption for a 2000-student high school under the following conditions:

a. Storage with minimum recovery rate

b. Storage with 15 m^3 maximum storage capacity

c. Monthly hot-water consumption

Solution:

a. With the minimum recovery rate of 0.16 mL/s per student (from Figure 32) for high schools, 320 mL/s recovery is required. The storage required is 11.5 L per student, or 2000 × 11.5 = 2.3 m^3. If 70% of the hot water is usable, the tank size is 2.3/0.7 = 32.9 m^3.

b. Net storage capacity is 0.7 × 15 = 10.5 m^3, or 5.25 L per student. From the curve, a recovery capacity of 0.41 mL/s per student or 2000 × 0.41 = 820 mL/s is required.

c. From Table 6, monthly hot-water consumption is 2000 students × 1.8 6.8 L per student per day × 22 days = 299 m^3.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat loss.

Table 13 can be used to determine the size of water-heating equipment from the number of fixtures. However, caution is advised when using this table, because its data are very old, taken well before the introduction of modern low-flow fixtures and appliances. Moreover, this method tends to provide systems having both high heating rates and significant quantities of storage, and provides a single combination of heating rate and storage, rather than a curve of workable combinations of heating rate and storage volume. To obtain the probable maximum demand, multiply the total quantity for the fixtures by the demand factor in line 19. Note that, as the number of fixtures becomes very small (e.g., for a water heater to serve a single small apartment), the demand (diversity) factors listed in Table 13 are no longer valid. In all cases, total demand is never less than the demand for the largest single fixture. The heater or coil should have a water-heating capacity equal to this probable maximum demand. The storage tank should have a capacity equal to the probable maximum demand multiplied by the storage capacity factor in line 20.

Example 7. Determine heater and storage tank size for an apartment building from a number of fixtures.

Solution:

60 lavatories × 7.6 = 456 L/h

30 bathtubs × 76 = 2280 L/h

30 showers × 114 = 3420 L/h

60 kitchen sinks × 38 = 2280 L/h

15 laundry tubs × 76 = 1140 L/h

Possible maximum demand = 9576 L/h

Probable maximum demand = 9576 × 0.30 = 2870 L/h

Heater or coil capacity = 2870/3600 = 0.80 L/s

Storage tank capacity = 2870 × 1.25 = 3590 L

Showers. In many housing installations such as motels, hotels, and dormitories, peak hot-water load is usually from shower use. Table 13 indicates the probable hourly hot-water demand and recommended demand and storage capacity factors for various types of buildings. Hotels could have a 3 to 4 h peak shower load. Motels require similar volumes of hot water, but peak demand may last for only a 2 h period. In some types of housing, such as barracks, fraternity houses, and dormitories, all occupants may take showers within a very short period. In this case, it is best to find the peak load by determining the number of shower heads and rate of flow per head; then estimate the length of time the shower will be on. It is estimated that the average shower time per individual is 7.5 min (Meier 1985).

Flow rate from a shower head varies depending on type, size, and water pressure. At 280 kPa water pressure, available shower heads have nominal flow rates of blended hot and cold water from about 160 to 380 mL/s (older designs). In multiple-shower installations, flow control valves on shower heads are recommended because they reduce flow rate and maintain it regardless of fluctuations in water pressure. Flow can usually be reduced to 50% of the manufacturer's maximum flow rating without adversely affecting the spray pattern of the shower head. Flow control valves are commonly available with capacities from 95 to 250 mL/s.

If the manufacturer's flow rate for a shower head is not available and no flow control valve is used, the following average flow rates may serve as a guide for sizing the water heater:

Small shower head 160 mL/s

Medium shower head 280 mL/s*

Large shower head 380 mL/s*

*These flow rates for medium and large shower heads are no longer allowed by statute, but some are still available.

Note that the maximum flow rate allowed by U.S. federal energy efficiency standards is 160 mL/s, as of 1992. However, higher-flowrate models are still sold. Note also that rated or allowed maximum flow rates for fixtures generally assume a mixture of hot and cold water, and thus do not represent solely hot-water use. Assumptions about supplied hot- and cold-water temperatures and mixed water temperatures must be made to determine probable amount of hot-water use (see Equation [17]).

Food Service. These establishments are required to provide a sufficient supply of hot water to meet the peak hot-water demand requirements set forth by the overseeing regulatory body, usually the county health department. Cities and counties adopt or modify state or federal hot-water sizing guidelines for food service establishments to meet the needs of their locality. The procedure for sizing water heaters for restaurants typically includes the following steps:

1. List all hot-water end-use fixtures by type and by count.
2. Characterize each fixture for maximum hot-water use per hour and per minute.
3. Calculate the peak hot-water demand for water heaters with and without storage.
4. Obtain the water heater temperature rise required for winter.
5. Calculate the minimum water heater input rate.
6. Select the water heater type, input rate, and storage capacity (in a few jurisdictions).

It is important to note that the hot-water requirements for various fixtures presented in Table 14 are based on various resources (see the table notes), which are currently used by food service facilities and health departments to size hot-water heaters. Some equipment flow data in these guidelines predates current low-flow fixtures used in kitchens. Specifically, the flow rate requirements for prerinse spray valves have dropped from 315 mL/s to a federally mandated maximum flow rate of 100 mL/s, and, similarly, flow rate requirements for aerators on public hand sinks have dropped from 140 mL/s to 30 mL/s.

Table 14 Hot-Water Requirements for Various Commercial Kitchen Uses

Equipment[a]	Storage, mL/s	Tankless, mL/s
Hand sink or lavatory	5.3	30
One-compartment food preparation or utility sink	5.3	125
Two-compartment food preparation or utility sink	11	125
Large three-compartment sanitation sink (610 × 610 × 360 mm	110[b]	125[c]
Standard three-compartment sanitation sink (460 × 460 × 250 mm)	44[b]	125[c]
Bar three-compartment sanitation sink (250 × 360 × 250 mm)	19[b]	125
Mop sink or can wash facility	16	125[c]
Prerinse spray valve	47	Varies
Dishwasher	Varies[d]	Varies

Source: CCDEH (1995), FDA (2000), NCPH (2001).

[a] Refer to manufacturer's specifications for other end-use fixtures that use hot water.

[b] Equation to calculate storage heater hot water demand requirements for sanitation sinks:

$$\text{mL/s} = \text{Sink size (mm}^3) \times \text{Number of compartments} \times 0.001\ (\text{mL/(h} \cdot \text{mm}^3) \div 3600\ \text{s/h}$$

Certain jurisdictions, including the FDA and North Carolina, use a compartment fill factor, which is 75% of the sink size, to calculate the hot water requirements of sanitation sinks.

[c] A flow rate of 320 mL/s is recommended for compartment sink or hose bibb fill operations.

[d] Certain jurisdictions, including the FDA and North Carolina, use a rack loading efficiency factor, which is 70% of the dishwasher manufacturer's listed hourly rinse water use, to calculate hot-water demand.

Table 15 Range in Water Heater Flow Rate Requirements to Satisfy Dishwasher Rinse Operation of Various Units

Type of Dishwasher	Flow Rate for Heaters Without Storage,[a] mL/s	Hourly Demand for Heaters with Storage,[b] mL/s

Undercounter (low-temperature)	130 to 280	23 to 68
Undercounter (high-temperature)	200 to 420	20 to 54
Door type (low-temperature)	120 to 320	35 to 72
Door type (high-temperature)	170 to 450	29 to 97
Rack conveyor (low-temperature)	80 to 300	80 to 300
Rack conveyor (high-temperature)	45 to 300	50 to 300
Flight conveyor (high-temperature)	65 to 380	60 to 380

[a] Based on flow rate during rinse operation period.

[b] Based on dishwasher operation at 100% of mechanical capacity.

Note that the sizing guidelines required by local mandate for commercial food service applications specify only the required heating rates; they do not address the storage volume requirements of storage water heaters. Because of this, it is not really possible to size storage water heaters with the information specified. Although for some types of storage water heaters it may be possible to provide the storage water heater heating rate specified, there is no way to know how large the tank needs to be with that information alone. More information is needed regarding the time spacing of draws throughout the day before adequate storage volume can be specified. It is possible to design or select storage water heating systems that will perform adequately but do not have as high a heating rate as may be specified in local mandates, as long as adequate amounts of storage are provided. In this regard, the outdated practice of specifying needed storage water heater heating requirements without regard to storage volume used is an impediment to use of newer higher efficiency technologies, such as gas- or electric heat pump water heaters and solar water heating systems. Such systems would normally be provided with lower heating rates and more storage when meeting loads, to minimize first costs.

The intent of the heating rate sizing guidelines for storage heaters is an attempt to ensure that hot water is available during operating hours to meet the food preparation and sanitation needs of the facility for food safety reasons. Thus, the food service sizing guideline is the minimum bar that some localities may accept for specified heating rates. However, this differs from the combination of heating rate and storage volume that may actually work for a given installation. The sizing guidelines are limited in that they only focus on calculating the energy input rate to the water heater without providing guidance on minimum hot-water storage requirements (except for North Carolina), and hot-water delivery performance considerations (e.g., performance limitations of tankless heaters with door-type dishwashers). The food safety sizing guidelines for water heaters also do not consider after-hours cleanup, when the peak hourly hot-water use occurs in some facilities; this may cause emptying of the tank on a nightly basis. Rapidly using hot water and filling the tank with cold water can cause thermal fatiguing of the tank, greatly reducing the operating life in gas storage heaters (Fisher-Nickel 2010). There is no current method for calculating the minimum storage requirement for a food service facility or sizing storage heaters based on the ratio of storage capacity and energy input rate. This is a difficult task, because hot-water use on an average daily, peak hourly, or per-minute basis greatly varies between food service facilities, especially in larger facilities, even of equal size and type. Variations in staff operating practices (e.g., after-hours store cleaning), equipment maintenance, and other operations between two identical facilities can cause large differences in hot-water consumption. This sizing guideline and associated examples are intended to clarify the prevailing food safety sizing guidelines, which in many cases are not comprehensive and are difficult to follow.

After the maximum flow rate has been calculated using Table 14, the required heater(s) may be sized using manufacturers' specification sheets that cross-reference temperature rise and flow rate, or using Equation (11):

$$q_i = Q_h c_p \rho \Delta t / \eta \quad (11)$$

where

q_i	=	heater input, W
Q_h	=	flow rate, mL/s
c_p	=	specific heat of water = 4.1868 kJ/(kg · K)
ρ	=	density of water = 1.0 kg/L
Δt	=	temperature rise, K
η	=	heater efficiency

Sizing water heater input rate in food service may require following local food safety department water-heater sizing guidelines, which typically provide end-use fixture flow rates, temperature rise, and heater efficiency values to calculate minimum flow rate or recovery rate. An alternative to using these input rate sizing guidelines requires the commercial kitchen to hire a professional engineer to submit for approval an alternative water-heater sizing calculation. This latter method is typically too costly and time consuming in the build-out or renovation of most commercial kitchens.

Dishwashers in food service facilities typically dictate the water heater outlet temperature required. Dishwashers generally require delivery of 60°C water for rinse operation, but inlet temperature can range from a minimum of {50°C for a low-temperature dishwasher to 82°C for a high-temperature dishwasher without a booster heater. For a typical hot-water system distribution line, heat losses require the water heater thermostat to be set at an elevated temperature (typically between 63 to 66°C) to deliver 60°C water to the dishwasher or booster heater.

In restaurants, bacteria are killed by rinsing washed dishes with 82 to 90°C water for several seconds. In addition, an ample supply of general-purpose hot water, usually at 60 to 65°C, is required for the wash cycle of dishwashers. Although a water temperature of 60°C is reasonable for dish washing in private dwellings, in public places, the NSF (e.g., *Standard* 3) or local health departments require 82 to 90°C water in the rinsing cycle. However, the NSF allows a lower temperature of 50 to 60°C when low temperature or fill and dump machines are used with the use of a chemical sanitizing rinse. The two-temperature hot-water requirements of food service establishments present special problems. The lower-temperature water is distributed for general use, but the 82°C water should be confined to the equipment requiring it and should be obtained by boosting the temperature. It is dangerous to distribute 82°C water for general use. ANSI/NSF *Standard* 3-2001 covers the design of dishwashers and water heaters used by restaurants.

The data provided in Table 15 shows the range of water heater flow rate and hourly hot-water demand requirements for various types of low- and high-temperature sanitizing dishwashers based on 100% operating capacity of the machines. Loading a dishwasher at 100% capacity is impractical in most commercial kitchens. Some local health departments assume a 70% operating rinse capacity for sizing dishwashers' hot-water demand, except for rackless-type conveyor machines where the fresh-water rinse is continually operating when the machine is in operation. Some dishwashers use only a cold-water supply for rinse and (with some models) for the tank fill, allowing them to operate without any connection to the hot-water line. These undercounter and door-type machines typically use integrated booster heaters and exhaust-air heat recovery to preheat the cold water for the next rinse cycle.

Examples 8, 9,and 10 demonstrate the use of Equation (11) in conjunction with Tables 14 and 15.

Example 8. Determine the maximum hot-water flow rate demand for tankless water heaters and the maximum hourly average hot-water flow rate demand for storage water heaters for a commercial kitchen with a one-compartment food preparation sink, one standard three-compartment sanitation sink, two hand sinks, two lavatories, one mop sink, one prerinse sink with a 70 mL/s spray valve, and one high-temperature door-type dishwasher (3.8 L/rack, 11 s rinse time, 57 racks/h) with a built-in 22 K temperature rise booster heater.

Solution: The end-use fixtures and hot-water demand requirements for sizing the heating rate of storage or tankless water heaters are shown in the following table:

Item	Flow Rate Required, mL/s	Recovery Rate Required, mL/s
One-comp. prep sink	125	5
Three-comp. sink	125	46
Hand sink (2)	65	11
Lavatory (2)	65	11
Mop sink	125	16
Prerinse sink	70	47
Dishwasher	340	60
Total requirements	915	196

The minimum flow rate for sizing the heating rate of a tankless water heater is 915 mL/s. Likewise, the minimum flow rate for sizing the heating rate of a storage water heater is 196 mL/s.

Example 9. Determine the energy input requirements (heating rate) for both a tankless and a storage water heater for the commercial kitchen described in Example 8. Examine both gas and electric resistance energy source options. Assume an operating efficiency of 70% for the noncondensing gas option, 85% condensing for the condensing gas option, 90% for the electric storage option, and 99% for the electric tankless option. Assume the design entering cold-water temperature (winter) is 10°C and the water heater outlet temperature is 66°C. This is a little higher than the 60°C required by the dishwasher booster heater, to account for piping heat losses.

Solution: The temperature rise required is 66 – 10 = 56 K. For a tankless water heater, the required heating rate using Equation (11) is computed as

$$q_i = (0.915\ \text{L/s})(1.0\ \text{kg/L})[4.1868\ \text{kJ/(kg·K)}](56\ \text{K}) = 215\ \text{kW}$$

Thus, for the 70% gas tankless option, the required energy input rate is 215/0.70 = 307 kW. It is common practice to install one or more 58 kW units in parallel in commercial facilities to meet minimum flow rate requirements. Using this approach, six standard-efficiency tankless units, each rated at 58 kW, are required to meet this load. For the 85% gas condensing tankless option, the required heating rate is 215/0.85 = 253 kW, requiring five 58 kW condensing tankless heaters. For the 99% electric tankless option, the required energy input rate is 215/0.99 = 217 kW. Four 54 kW or six 36 kW electric resistance tankless heaters are required to meet the hot-water demand.

Because tankless water heaters have no storage volume, these heating rates are adequate for use in specifying appropriate water heaters.

Sizing tankless heaters using manufacturers' specification sheets data on maximum flow rate at a given temperature rise is a common approach, because the data are readily provided. Flow rate data varies slightly among manufacturers of similar products at the same input rate based on the efficiency of the unit. A 58 kW standard-efficiency heater typically provides a maximum of 210 mL/s of water at a 56 K temperature rise, whereas a condensing heater provides 240 mL/s. To meet the flow requirements of 915 mL/s for this facility, five standard-efficiency 58 kW units installed in parallel for a combined input rate of 292 kW are required to meet the load by providing a maximum combined flow rate of 1040 mL/s. To meet the flow requirements with condensing high-efficiency tankless heaters, four 58 kW units for a combined input rate of 233 kW are required, for a maximum combined flow rate of 960 mL/s. It is important to note that using the manufacturer's stated maximum flow rate at a given temperature rise to calculate the number of tankless units based on the maximum flow rate calculation of 915 mL/s is a less conservative approach, because it relies on the rated thermal efficiency of the heater instead of the typical operating efficiency.

For the storage water heaters, the required heating rate is computed as

$$q_i = (0.196 \text{ L/s})(1.0 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)}](56 \text{ K}) = 46 \text{ kW}$$

Thus, for the 70% gas storage water heater, the required heating rate is 46/0.70 = 66 kW. For the 85% gas condensing storage water heater, the required heating rate is 46/0.85 = 54 kW. For the 90% electric resistance storage water heater, the required heating rate is 46/0.90 = 51 kW.

Note that this information in insufficient to properly specify a storage water heater, because a method for calculating the minimum storage volume is needed. Moreover, once storage is incorporated, note that the loads can be met by using smaller heating rates than those computed here, using larger storage tanks. In this respect, the heating rates mandated by a typical health department become a barrier to using higher-efficiency equipment, such as heat pump water heaters or solar water heating, whose heating capacities are more expensive than standard efficiency equipment, and whose cost-effective system designs therefore favor smaller heating rates and larger storage volumes. Although this is true, the majority of water heaters in commercial kitchens are specified using the food safety guidelines to calculate the minimum input rate of conventional gas or electric water heaters. In doing so, one or more storage heaters may be selected to meet this total requirement. Typically, one 73 kW gas storage heater (or two 37 kW units) rated at 80% thermal efficiency is chosen. An energy-efficient approach is to select a high-efficiency condensing water heater rated at 95% thermal efficiency, which is assumed to be operating at 85% operating efficiency in this kitchen with continuous recirculation. A 58 kW condensing gas storage heater will meet the requirements for this facility and is a better value, because it reduces operating costs and is competitive on first costs. One 54 kW or two 27 kW electric resistance storage heaters could be selected from manufacturers' specification sheets to meet the hot-water demand.

Example 10. For the commercial kitchen described in Example 8, what is the condensing storage water heater input rating if the facility chooses to install a dishwasher that only requires a cold-water hookup? Assume that the facility can benefit by reducing the required outlet temperature by 11 K from 66°C. Also assume that, by removing the need for continuous recirculation, this measure improves the operating efficiency from a nominal 85% to 90%.

Solution: The total hot-water demand calculated in Example 8 drops from 196 mL/s to 136 mL/s when the hot-water demand of the dishwasher on the centralized water heater is eliminated. For the storage water heaters, the required heating rate is computed as

$$q_i = (0.136 \text{ L/s})(1.0 \text{ kg/L})[4.1868 \text{ kJ/(kg·K)}](44 \text{ K}) = 25 \text{ kW}$$

For the 90% gas condensing storage water heater, the required heating rate is 25/0.90 = 28 kW. One 29 kW gas condensing storage heater can be selected to meet the hot water demand using the food safety input rate sizing guidelines. Also, dishwashers that have only a cold water feed typically depend on heat recovery systems to preheat the incoming cold water from the exhaust or drainwater waste streams to a temperature of 43°C. They rely on larger secondary heating systems commonly referred to as booster heaters to heat the water to the 82°C sanitizing rinse temperature on a high-temperature machine. This requires the addition of a 39 K rise booster heater instead of a conventional 22 K booster heater that would be used in conjunction with entering 60°C water from the primary water heater.

Schools. Service water heating in schools is needed for janitorial work, lavatories, cafeterias, shower rooms, and sometimes swimming pools. Hot water used in cafeterias is about 70% of that usually required in a commercial restaurant serving adults and can be estimated by the method used for restaurants. Where NSF sizing is required, follow *Standard* 5. Shower and food service loads are not ordinarily concurrent. Each should be determined separately, and the larger load should determine the size of the water heater(s) and the tank. Provision must be made to supply 82°C sanitizing rinse. The booster must be sized according to the temperature of the supply water. If feasible, the same water can be used for both needs. If the distance between the two points of need is great, a separate water heater should be used. A separate heater system for swimming pools can be sized as outlined in the section on Swimming Pools/Health Clubs.

Domestic Coin-Operated Laundries. Small domestic machines in coin laundries or apartment house laundry rooms have a wide range of draw rates and cycle times. Domestic machines provide a wash water temperature (normal) as low as 50°C. Some manufacturers recommend a temperature of 70°C; however, the average appears to be 60°C. Hot-water sizing calculations must ensure a supply to both the instantaneous draw requirements of a number of machines filling at one time and the average hourly requirements.

The number of machines drawing at any one time varies widely; the percentage is usually higher in smaller installations. One or two customers starting several machines at about the same time has a much sharper effect in a laundry with 15 or 20 machines than in one with 40 machines. Simultaneous draw may be estimated as follows:

1 to 11 machines 100% of possible draw

12 to 24 machines 80% of possible draw

25 to 35 machines 60% of possible draw

36 to 45 machines 50% of possible draw

Possible peak draw can be calculated from

$$F = 1000NPV_f/T \tag{12}$$

where

F	=	peak draw, mL/s
N	=	number of washers installed
P	=	number of washers drawing hot water divided by N
V_f	=	quantity of hot water supplied to the machine during hot-wash fill, L
T	=	wash fill period, s

Recovery rate can be calculated from

$$R = (1000NV_f)/[60(\theta + 10)] = 16.7\ NV_f/(\theta + 10) \tag{13}$$

where

R	=	total hot water (machines adjusted to the hottest water setting), mL/s
θ	=	actual machine cycle time, min

Note: (θ + 10) is the cycle time plus 10 min for loading and unloading.

Commercial Laundries. Commercial laundries generally use a storage water heater. The water may be softened to reduce soap use and improve quality. The trend is toward installing high-capacity washer-extractor wash wheels, resulting in high peak demand.

Sizing Data. Laundries can normally be divided into five categories. The required hot water is determined by the mass of the material processed. Average hot-water requirements at 82°C are

Institutional 4.6 mL/(kg · s)

Commercial 4.6 mL/(kg · s)

Linen supply 5.8 mL/(kg · s)

Industrial 5.8 mL/(kg · s)

Diaper 5.8 mL/(kg · s)

Total mass of the material times these values give the average hourly hot-water requirements. The designer must consider peak requirements; for example, a 270 kg machine may have a 1.25 L/s average requirement, but the peak requirement could be 22 L/s.

In a multiple-machine operation, it is not reasonable to fill all machines at the momentary peak rate. Diversity factors can be estimated by using 1.0 of the largest machine plus the following balance:

	Total number of machines				
	2	3 to 5	6 to 8	9 to 11	12 and over
1.0 +	0.6	0.45	0.4	0.35	0.3

For example, four machines have a diversity factor of 1.0 + 0.45 = 1.45.

Types of Systems. Service water-heating systems for laundries are pressurized or vented. The pressurized system uses city water pressure, and the full peak flow rates are received by the softeners, reclaimer, condensate cooler, water heater, and lines to the wash wheels. Flow surges and stops at each operation in the cycle. A pressurized system depends on an adequate water service.

The vented system uses pumps from a vented (open) hot-water heater or tank to supply hot water. The tank's water level fluctuates from about 150 mm above the heating element to a point 300 mm from the top of the tank; this fluctuation defines the working volume. The level drops for each machine fill, and makeup water runs continuously at the average flow rate and water service pressure during the complete washing cycle. The tank is sized to have full working volume at the beginning of each cycle. Lines and softeners may be sized for the average flow rate from the water service to the tank, not the peak machine fill rate as with a closed, pressurized system.

Waste heat exchangers have continuous flow across the heating surface at a low flow rate, with continuous heat reclamation from the wastewater and flash steam. Automatic flow-regulating valves on the inlet water manifold control this low flow rate. Rapid fill of machines increases production (i.e., more batches can be processed).

Heat Recovery. Commercial laundries are ideally suited for heat recovery because 58°C wastewater is discharged to the sewer. Fresh water can be conservatively preheated to within 8 K of the wastewater temperature for the next operation in the wash cycle. Regions with an annual average temperature of 13°C can increase to 50°C the initial temperature of fresh water going into the hot-water heater. For each litre or kilogram per hour of water preheated 37 K (13 to 50°C), heat reclamation and associated energy savings is 155 kW.

Flash steam from a condensate receiving tank is often wasted to the atmosphere. Heat in this flash steam can be reclaimed with a suitable heat exchanger, to preheat makeup water to the heater by 5 to 10 K above the existing makeup temperature.

Swimming Pools/Health Clubs. The desirable temperature for swimming pools is 27°C. Most manufacturers of water heaters and boilers offer specialized models for pool heating; these include a pool temperature controller and a water bypass to prevent condensation. The water-heating system is usually installed before the return of treated water to the pool. A circulation rate to generate a change of water every 8 h for residential pools and 6 h for commercial pools is acceptable. An indirect heater, in which piping is embedded in the walls or floor of the pool, has the advantage of reduced corrosion, scaling, and condensation because pool water does not flow through the pipes, but its disadvantage is the high initial installation cost.

The installation should have a pool temperature control and a water pressure or flow safety switch. The temperature control should be installed at the inlet to the heater; the pressure or flow switch can be installed at either the inlet or outlet, depending on the manufacturer's instructions. It affords protection against inadequate water flow.

Sizing should be based on four considerations:

- Conduction through the pool walls
- Convection from the pool surface
- Radiation from the pool surface
- Evaporation from the pool surface

Except in aboveground pools and in rare cases where cold groundwater flows past the pool walls, conduction losses are small and can be ignored. Because convection losses depend on temperature differentials and wind speed, these losses can be greatly reduced by installing windbreaks such as hedges, solid fences, or buildings.

Radiation losses occur when the pool surface is subjected to temperature differentials; these frequently occur at night, when the sky temperature may be as much as 45 K below ambient air temperature. This usually occurs on clear, cool nights. During the daytime, however, an unshaded pool receives a large amount of radiant energy, often as much as 30 kW. These losses and gains may offset each other. An easy method of controlling nighttime radiation losses is to use a floating pool cover; this also substantially reduces evaporative losses.

Evaporative losses constitute the greatest heat loss from the pool (50 to 60% in most cases). If it is possible to cut evaporative losses drastically, the pool's heating requirement may be cut by as much as 50%. A floating pool cover can accomplish this.

A pool heater with an input great enough to provide a heat-up time of 24 h would be the ideal solution. However, it may not be the most economical system for pools that are in continuous use during an extended swimming season. In this instance, a less expensive unit providing an extended heat-up period of as much as 48 h can be used. Pool water may be heated by several methods. Fuel-fired water heaters and boilers, electric boilers, tankless electric circulation water heaters, air-source heat pumps, and solar heaters have all been used successfully. Air-source heat pumps and solar heating systems are often used to extend a swimming season rather than to allow intermittent use with rapid pickup.

The following equations provide some assistance in determining the area and volume of pools.

Elliptical

Area = $3.14AB$

A = Short radius

B = Long radius

Volume = Area × Average Depth

Kidney Shaped

Area = $0.45L(A+B)$ (approximately)

L = Length

A = Width at one end

B = Width at other end

Volume = Area × Average Depth

Oval (for circular, set $L = 0$)

Area = $3.14R^2 + LW$

L = Length of straight sides

W = Width or $2R$

R = Radius of ends

Volume = Area × Average Depth

Rectangular

Area = LW

L = Length

W = Width

Volume = Area × Average Depth

The following is an effective method for heating outdoor pools. Additional equations can be found in Chapter 6.

1. Obtain pool water capacity, in cubic metres.
2. Determine the desired heat pickup time in hours.
3. Determine the desired pool temperature. If not known, use 27°C.
4. Determine the average temperature of the coldest month of use.

The required heater output q_t can now be determined by the following equations:

$$q_1 = \rho c_p V(t_f - t_i)/\theta \times 3600 \text{ s/h} \quad (14)$$

where

q_1	=	pool heat-up rate, kW
ρ	=	density of water = 998 kg/m^3
c_p	=	specific heat of water = 4.1868 kJ/(kg · K)
V	=	pool volume, m^3
t_f	=	desired temperature (usually 27°C)
t_i	=	initial temperature of the pool, °C
θ	=	pool heat-up time, h

$$q_2 = UA(t_p - t_a) \quad (15)$$

where

q_2	=	heat loss from the pool surface, kW
U	=	surface heat transfer coefficient = 0.060 kW/(m^2 · K)
A	=	pool surface area, m^2
t_p	=	pool temperature, °C
t_a	=	ambient temperature, °C

$$q_t = q_1 + q_2 \quad (16)$$

Notes: These heat loss equations assume a wind velocity of 5 to 8 km/h. For pools sheltered by nearby fences, dense shrubbery, or buildings, an average wind velocity of less than 5.6 km/h can be assumed. In this case, use 75% of the values calculated by Equation (15). For a velocity of 8 km/h, multiply by 1.25; for 16 km/h, multiply by 2.0.

Because Equation (15) applies to the coldest monthly temperatures, results calculated may not be economical. Therefore, a value of one-half the surface loss plus the heat-up value yields a more viable heater output figure. Heater input then equals output divided by fuel source efficiency.

Whirlpools and Spas. Hot-water requirements for whirlpool baths and spas depend on temperature, fill rate, and total volume. Water may be stored separately at the desired temperature or, more commonly, regulated at the point of entry by blending. If rapid filling is desired, provide storage at least equal to the volume needed; fill rate can then be varied at will. An alternative is to establish a maximum fill rate and provide an instantaneous water heater that can handle the flow.

Industrial Plants. Hot water (potable) is used in industrial plants for cafeterias, showers, lavatories, gravity sprinkler tanks, and industrial processes. Employee cleanup load is usually heaviest and not concurrent with other uses. Other loads should be checked before sizing, however, to be certain that this is true.

Employee cleanup load includes (1) wash troughs or standard lavatories, (2) multiple wash sinks, and/or (3) showers. Hot-water requirements for employees using standard wash fixtures can be estimated at 3.8 L of hot water for each clerical and light-industrial employee per work shift and 7.6 L for each heavy-industrial worker.

For sizing purposes, the number of workers using multiple wash fountains is disregarded. Hot-water demand is based on full flow for the entire cleanup period. This usage over a 10 min period is indicated in Table 16. The shower load depends on the flow rate of the shower heads and their length of use. Table 16 may be used to estimate flow based on a 15 min period.

Water heaters used to prevent freezing in gravity sprinkler or water storage tanks should be part of a separate system. The load depends on tank heat loss, tank capacity, and winter design temperature.

Table 16 Hot-Water Usage for Industrial Wash Fountains and Showers

	Multiple Wash Fountains	Showers	
Type	**L of 60°C Water Required for 10 min Period[a]**	**Flow Rate, mL/s**	**L of 60°C Water Required for 15 min Period[b]**
910 mm Circular	150	190	110
Semicircular	83	250	150
1370 mm Circular	250	320	185
Semicircular	150	380	220

[a] Based on 43°C wash water and 5°C cold water at average flow rates.

[b] Based on 40°C shower water and 5°C cold water.

Table 17 Water Heater Sizing for Ready-Mix Concrete Plant (Input and Storage Tank Capacity to Supply 65°C Water at 4°C Inlet Temperature)

Truck Capacity, m³	Water Heater Storage Tank Volume, L	Time Interval Between Trucks, min*					
		50	35	25	10	5	0
		Water Heater Capacity, kW					
4.6	1630	134	179	230	403	536	809
5.7	1860	154	205	264	463	615	923
6.9	2130	174	232	299	524	697	1049
8.4	2430	201	268	344	604	803	1207

* This table assumes 10 min loading time for each truck. Thus, for a 50 min interval between trucks, it is assumed that 1 truck/h is served. For 0 min between trucks, it is assumed that one truck loads immediately after the truck ahead has pulled away. Thus, 6 trucks/h are served. It also assumes each truck carries a 450 L storage tank of hot water for washing down at the end of dumping the load. This hot water is drawn from the storage tank and must be added to the total hot water demands. This has been included in the table.

Process hot-water load must be determined separately. Volume and temperature vary with the specific process. If the process load occurs at the same time as the shower or cafeteria load, the system must be sized to reflect this total demand. In some cases, it may be preferable to use separate systems, depending on the various load sizes and distance between them.

Ready-Mix Concrete. In cold weather, ready-mix concrete plants need hot water to mix the concrete so that it will not be ruined by freezing before it sets. Operators prefer to keep the mix at about 21°C by adding hot water to the cold aggregate. Usually, water at about 65°C is considered proper for cold weather. If the water temperature is too high, some of the concrete will flash set.

Generally, 150 L of hot water per cubic metre of concrete mix is used for sizing. To obtain the total hot-water load, this number is multiplied by the number of trucks loaded each hour and the capacity of the trucks. The hot water is dumped into the mix as quickly as possible at each loading, so ample hot-water storage or large heat exchangers must be used. Table 17 shows a method of sizing water heaters for concrete plants.

Sizing Boilers for Combined Space and Water Heating

When service water is heated indirectly by a space heating boiler, Figure 34 may be used to determine the additional boiler capacity required to meet the recovery demands of the domestic water-heating load. Indirect heaters include immersion coils in boilers as well as heat exchangers with space-heating media.

Because the boiler capacity must meet not only the water supply requirement but also the space heating loads, Figure 34 indicates the reduction of additional heat supply for water heating if the ratio of water-heating load to space-heating load is low. This reduction is possible because

- Maximum space-heating requirements do not occur at the time of day when the maximum peak hot-water demands occur.
- Space-heating requirements are based on the lowest outdoor design temperature, which may occur for only a few days of the total heating season.
- An additional heat supply or boiler capacity to compensate for pickup and radiation losses is usual. The pickup load cannot occur at the same time as the peak hot-water demand because the building must be brought to a comfortable temperature before the occupants use hot water.

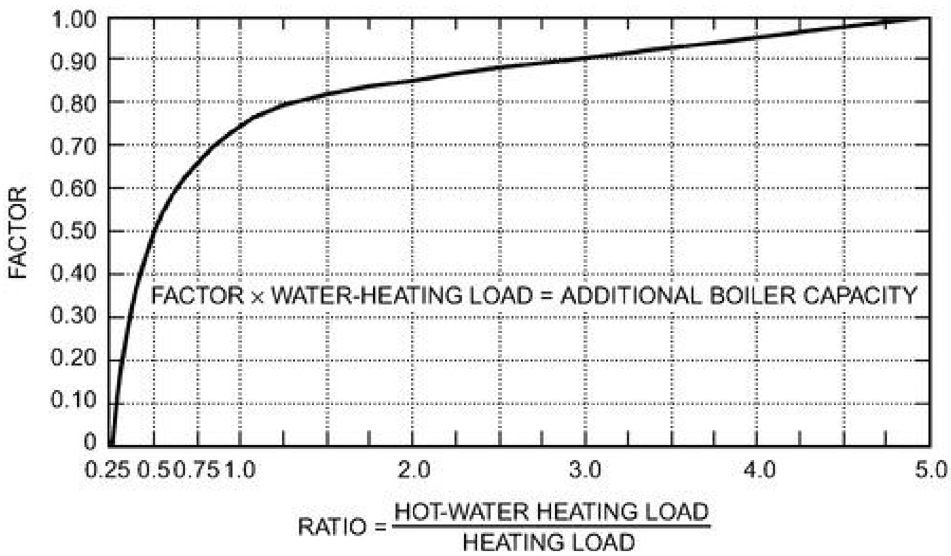

Figure 34. Sizing Factor for Combination Heating and Water-Heating Boilers

The factor obtained from Figure 34 is multiplied by the peak water-heating load to obtain the additional boiler output capacity required.

For reduced standby losses in summer and improved efficiency in winter, step-fired modular boilers may be used. Units not in operation cool down and reduce or eliminate jacket losses. Heated boiler water should not pass through an idle boiler. Figure 35 shows a typical modular boiler combination space- and water-heating arrangement.

Table 18 Needed Tankless Water Heater Output Heat Rates, kW[*]

	Temperature Rise						
Flow Rate, mL/s	**6 K**	**14 K**	**28 K**	**31 K**	**42 K**	**43 K**	**56 K**
6.3	0.15	0.37	0.74	0.81	0.99	1.14	1.48
31.5	0.74	1.85	3.69	4.06	164.95	5.69	7.39
63.1	1.48	3.69	7.39	8.12	9.92	11.4	14.8
94.6	2.22	5.54	11.1	12.2	14.83	17.1	22.2
126	2.95	7.39	14.8	16.2	19.83	22.8	29.5
158	3.69	9.23	18.5	20.3	24.75	28.4	36.9
189	4.43	11.1	22.2	24.4	101,304 26.99	34.1	44.3
221	5.17	12.9	25.8	28.4	34.66	39.8	51.7
252	5.91	14.8	29.5	32.5	39.57	45.5	59.1
284	6.65	16.6	33.2	36.6	44.58	51.2	66.5
315	7.39	18.5	36.9	40.6	49.49	56.9	73.9
379	8.86	22.2	44.3	48.7	59.41	68.2	88.6
442	10.3	25.8	51.7	56.9	69.23	79.6	103.4
505	11.8	29.5	59.1	65.0	79.15	91.0	118.2
568	13.3	33.2	66.5	73.1	89.07	102.4	132.9
631	14.8	36.9	73.9	81.2	337,68098.98	113.7	147.7

[*] Divide table values by input efficiency to determine required heat input rate.

Typical Control Sequence for Indirect Water Heaters

1. Any control zone or indirectly fired water heater thermostat (e.g., T_{z_1} or T_{wh} in Figure 35) starts its circulating pump and supplies power to boiler no. 1 control circuit.
2. If T_1 is not satisfied, burner is turned on, boiler cycles as long as any circulating pump is on.
3. If after 5 min T_A is not satisfied, V_1 opens and boiler no. 2 comes on line.
4. If after 5 min T_B is not satisfied, V_2 opens and boiler no. 3 comes on line.
5. If T_C is satisfied and two boilers or fewer are firing for a minimum of 10 min, V_2 closes.
6. If T_B is satisfied and only one boiler is firing for a minimum of 10 min, V_1 closes.
7. If all circulating pumps are off, boiler no. 1 shuts down.

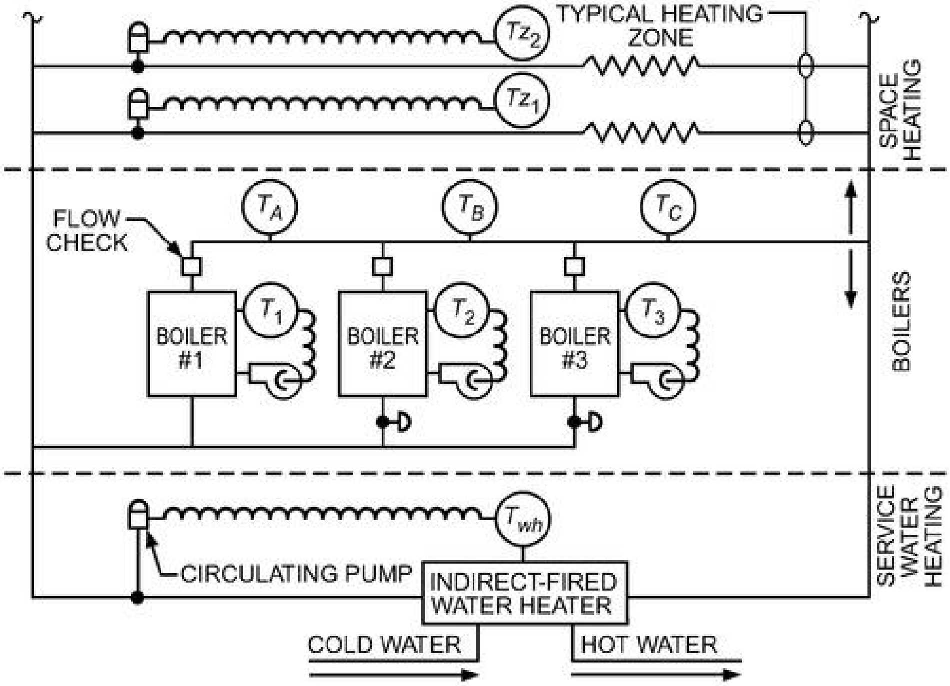

Figure 35. Typical Modular Boiler for Combined Space and Water Heating

ASHRAE/IES *Standards* 90.1 and 90.2 discuss combination service water-heating/space-heating boilers and establish restrictions on their use. The ASHRAE/IES *Standard* 100 section on Service Water Heating also has information on this subject.

Sizing Tankless Water Heaters

Although tankless water heaters are sometimes also referred to as instantaneous water heaters, in this chapter the two types are distinct. Larger instantaneous water heaters for bigger commercial, institutional, and industrial applications may still have some water storage tank volume, even though their ratio of heating rate divided by storage volume is large. Many smaller commercial and residential systems only contain a volume of water sufficient to fill the chambers or tubing where the heating is done; they do not incorporate storage tanks, and are truly tankless as the term is used here. Note that all tankless heaters are instantaneous water heaters, but not all instantaneous water heaters are tankless. Another distinction between storage and tankless water heaters is that storage water heaters normally use thermostats to keep the stored water hot and immediately available for use, while tankless water heaters are not kept hot, but rather only turn on to heat water when flow is detected.

Tankless water heaters offer potential efficiency advantages over tank-type units for several reasons. Because they do not store heated water, they have low standby energy loss (typically, only a small amount of electricity to run controls). This energy savings potential can be significant for low-use applications. Another potential advantage is that the lack of a storage tank means they are much smaller than tank-type units and can more easily be located close to points of use (especially electric tankless units). Locating units close to points of use reduces energy losses in the hot-water distribution system, sometimes substantially. This ease of positioning may also make it easier to use more than one water heater, reducing hot-water distribution system heat losses still further by eliminating even more piping.

There are many good applications of both electric and fossil-fired tankless water heaters in residences, commercial, institutional, and industrial settings. Tankless water heaters are especially useful for providing more localized heating in point-of-use or near-point-of-use applications because they do not take up much space. In general, tankless water heaters are designed to completely heat cold water in one pass through the heater. There are exceptions, however, because some models with advanced controls can also heat prewarmed water by controllable amounts. See the discussion below about modulating heat input rates.

Table 19 Hot-Water Demand in Fixture Units (60°C Water)

	Apartments	Club	Gymnasium	Hospital	Hotels and Dormitories	Industrial Plant	Office Building	School	YMCA
Basin, private lavatory	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Basin, public lavatory	—	1	1	1	1	1	1	1	1
Bathtub	1.5	1.5	—	1.5	1.5	—	—	—	—
Dishwasher*	1.5	Five fixture units per 250 seating capacity							
Therapeutic bath	—	—	—	5	—	—	—	—	—
Kitchen sink	0.75	1.5	—	3	1.5	3	—	0.75	3
Pantry sink	—	2.5	—	2.5	2.5	—	—	2.5	2.5
Service sink	1.5	2.5	—	2.5	2.5	2.5	2.5	2.5	2.5

Shower	1.5	1.5	1.5	1.5	1.5	3.5	—	1.5	1.5
Circular wash fountain	—	2.5	2.5	2.5	—	4	—	2.5	2.5
Semicircular wash fountain	—	1.5	1.5	1.5	—	3	—	1.5	1.5

Note: Data predate modern low-flow fixtures and appliances.

* See Water-Heating Terminology section for definition of fixture unit.

Tankless water heaters generally have some sort of flow detection method (e.g., a flow switch or method of differential temperature measurement that indicates flow is occurring). Water heating only begins once water flow is confirmed. Outlet temperature from tankless water heaters is determined by the flow rate, entering cold-water temperature, and applied heating rate. Simpler systems do not actively control outlet temperature, other than to turn off the heat input if exit temperature exceeds a set value. These systems are more likely to specify the use of water flow restrictors to restrict flow through the units to minimize undesirably cool water exiting the units.

Systems with more advanced controls continuously monitor the exit water temperature and modulate the heat input and/or water flow rate to maintain the specified outlet temperature. Advanced electric tankless water heaters modulate power to the heating elements, either in steps (multiple heating elements) or by varying the voltage and/or current supplied to the heating elements, or both. Advanced fossil-fired tankless water heaters, which are available in both natural-gas- and propane-fired versions, modulate the heating rate by either modulating heat input in steps (e.g. using multiple burners), or by modulating gas flow rate to the burner(s), or some combination of the two. These designs can be used as booster heaters or in recirculated heating systems (i.e., they can work well with prewarmed entering water temperatures) because they can better control exit temperature.

One of the most important tankless water heater sizing considerations is having adequate heat input rate to heat the desired flow rate of water by a temperature rise needed to make the water warm enough to use. Table 18 shows the necessary heat input rate (not considering heat input efficiency: divide table values by heat input efficiency in decimal form [e.g., 0.8 for some fossil-fired heaters]) to determine total energy input rate required for tankless water heaters versus flow rate and needed temperature rise. The heating rates shown are computed using Equation (1).

Note that 40°C is about the minimum acceptable temperature for human use at fixtures. Accounting for heat loss in piping and/or when atomizing droplets in a showerhead, 43°C is a more typical requirement. The needed temperature rise in a cold climate where the entering cold-water temperature may be 2°C would thus be 43°C – 2°C = 41 K; in a warm climate where the entering cold water temperature may be 29°C, the temperature rise would be 43°C – 29°C = 14 K. For comparison, the temperature rise specified in the U.S. federal water heater testing and rating procedure is 57°C – 14°C = 43°C, and DOE (2014) revised this value downward to 52°C – 14°C = 38°C. For reference, typical flow rate ranges are as follows:

- Hand-washing sinks: 0.01 to 0.6 L/s
- Showers: 0.05 to 0.16 L/s
- Bathtub fill rates: 0.06 to 0.38 L/s
- Dishwasher fill rates: 0.06 to 0.19 L/s
- Clothes-washing machine fill rates: 0.06 to 0.38 L/s
- Residential whole-house recurring peak rates: around 0.19 to 0.25 L/s
- Residential whole-house severe-peak flow rates: 0.38 to 0.5 L/s

As can be seen from Table 18, whole-house tankless water heaters need to be able to provide heating rates on the order of 22 to 44 kW in all but the warmest climates. Note, however, that in single-family residential applications, users have the opportunity to learn what works and what does not, and are likely to adjust their hot-water use habits somewhat to obtain adequately hot water from whatever water-heating system is used. They could do this for example, by avoiding hot-water use from multiple fixtures simultaneously, and reducing demanded flow rates.

An important issue in the sizing of tankless water heaters is thus what peak hot-water energy rate load to design for. It is generally acceptable to design the water-heating system to meet a peak hot-water load (in terms of energy rate needed, not just water flow rate needed) that is not exceeded by 97.5% of all draws. The difficulty in sizing whole-house tankless water heaters comes in predicting how draws will coincide to create the peak energy demand rate. This peak coincident energy demand rate must be estimated by the person sizing the system. Research (Buchberger et al. 2015) provided hot-water draw information from a statistically large number of residential test sites, allowing estimation of probabilities of various types of draws occurring versus time of day, probabilities of how such draws may overlap in time within and between households, and normal ranges of flow rates and total volumes for the various types of draws. Sizing recommendations are easier with storage-type water heaters because their sizing is done more based on integrated total energy requirements, and is not highly dependent on knowledge of peak flow rates.

An issue related to proper sizing of tankless water heaters is the size of fuel piping and electrical service needed. Because gas-fired tankless water heaters must have significantly higher fuel burn rates than typical tank-types, larger gas piping may be required. The same is true for electric tankless water heaters, where a whole-house unit may require larger wiring and often additional (multiple) circuit breakers. Consequently, large tankless water heaters, both gas and electric, can in some cases require a service entrance upgrade. Notably, diversified electrical demand for large numbers of electric tankless water heaters is not much different (generally a little lower) than tank types, because of the lower number of tankless water heaters that are on at any point in time compared to tank types. However, as number of users on an electrical line decreases, demand diversity decreases, which can result in increased electrical demand compared to tank types as the number of users on the line decreases to fairly few. The number that "few" represents varies with size of the tankless units. Hiller (2017) found that diversified electrical demand of 28 kW tankless water heaters in residences was similar to that of 4.5 kW storage water heaters when number of households exceeded 2 to 15, depending on averaging time interval.

Sizing Instantaneous and Semi-Instantaneous Water Heaters

The methods for sizing storage water-heating equipment should not be used for instantaneous and semi-instantaneous heaters. The following is based on the Hunter (1941) method for sizing hot- and cold-water piping, with diversity factors applied for hot water and various building types. (Caution: the Hunter curve and fixture unit/fixture count methods of water heating system sizing come from very old data that predates the use of water and energy efficient fixtures and appliances. Moreover, these sizing methods are intended for sizing of instantaneous [greater than 0.3 kW heating rate per litre of storage] and semi-instantaneous (large heating rates, but with a bit more storage), not for sizing systems with more significant amounts of storage. As a result, these sizing methods only provide one workable combination of heating rate plus storage volume, as opposed to a continuous curve of workable heating rate plus storage combinations. The sizing combinations determined using these methods should work, but have a tendency to specify higher heating rates than necessary compared to sizing using modern data and techniques. These sizing techniques remain in this chapter because there is currently no better data for some of the building types.)

Fixture units (Table 19) are assigned to each fixture using hot water and totaled. Maximum hot-water demand is obtained from Figures 36 or 37 by matching total fixture units to the curve for the type of building. Special consideration should be given to applications involving periodic use of shower banks, process equipment, laundry machines, etc., as may occur in field houses, gymnasiums, factories, hospitals, and other facilities. Because these applications could have all equipment on at the same time, total hot-water capacity should be determined and added to the maximum hot-water demand from the modified Hunter curves. Often, the temperature of hot water arriving at fixtures is higher than is needed, and hot and cold water are mixed together at the fixture to provide the desired temperature.

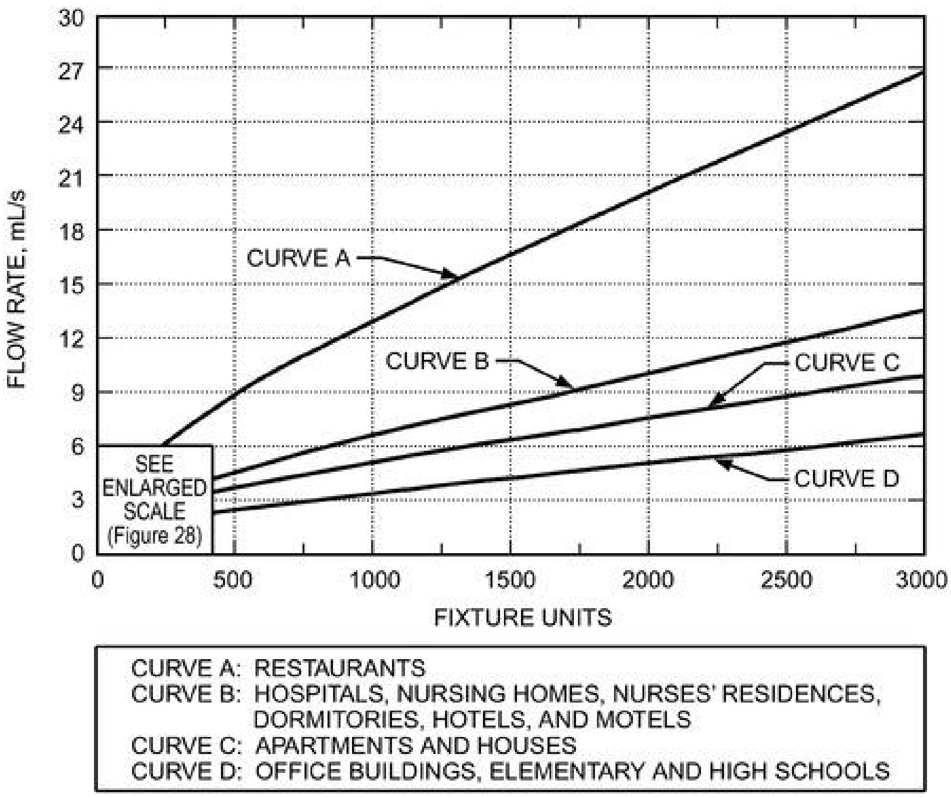

Figure 36. Modified Hunter Curve for Calculating Hot-Water Flow Rate (Data predate modern low-flow fixtures and appliances)

Table 20 Preliminary Hot-Water Demand Estimate

Type of Building	Fixture Units
Hospital or nursing home	2.50 per bed
Hotel or motel	2.50 per room
Office building	0.15 per person
Elementary school	0.30 per student*
Junior and senior high school	0.30 per student*

Apartment house	3.00 per apartment

* Plus shower load (in fixture units).

Equation (17), derived from a simple energy balance on mixing hot and cold water, shows the ratio of hot-water flow to desired end-use flow for any given hot, cold, and mixed end-use temperatures.

$$\text{Hot-water flow rate} = \frac{(\text{Mixed-temperature flow rate})(T_{mixed} - T_{cold})}{(T_{hot} - T_{cold})} \quad (17)$$

Once the actual hot-water flow rate is known, the heater can then be selected for the total demand and total temperature rise required. For critical applications such as hospitals, multiple heaters with 100% reserve capacity are recommended. Consider multiple heaters for buildings in which continuity of service is important. The minimum recommended size for semi-instantaneous heaters is 0.65 L/s, except for restaurants, for which it is 0.95 L/s. When system flow is not easily determined, the heater may be sized for full flow of the piping system at a maximum speed of 3 m/s. Heaters with low flows must be sized carefully, and care should be taken in the estimation of diversity factors. Unusual hot-water requirements should be analyzed to determine whether additional capacity is required. One example is a dormitory in a military school, where all showers and lavatories are used simultaneously when students return from a drill. In this case, the heater and piping should be sized for full system flow.

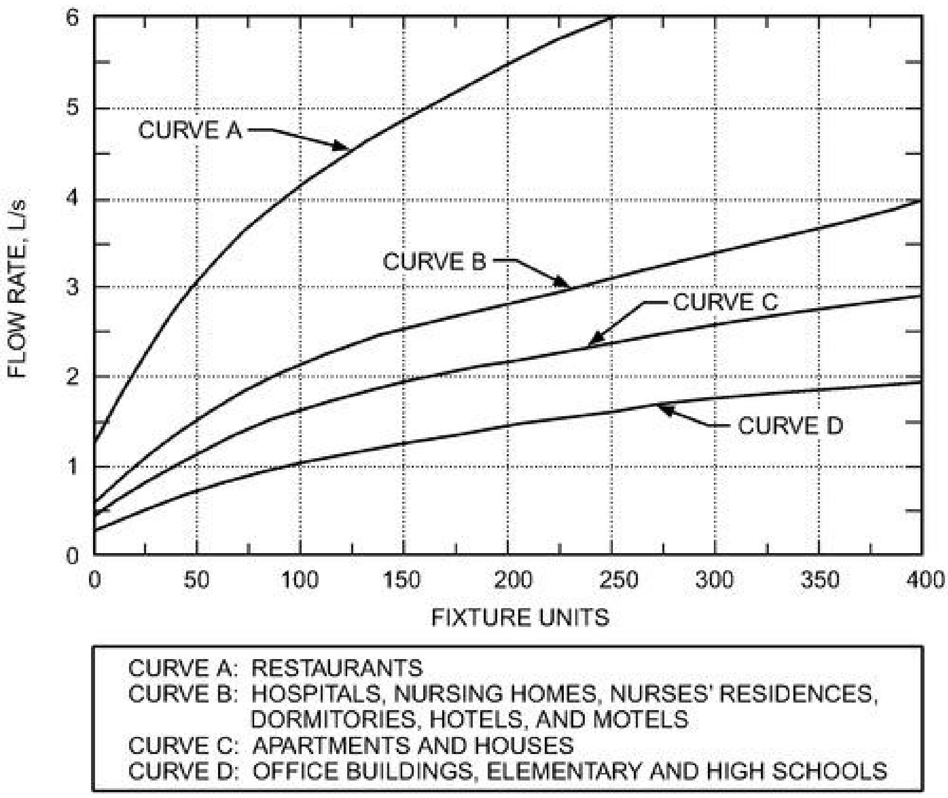

Figure 37. Enlarged Section of Figure 36 (Modified Hunter Curve) (Data predate modern low-flow appliances.)

Whereas the fixture count method bases heater size of the diversified system on hot-water flow, hot-water piping should be sized for full flow to the fixtures. Recirculating hot-water systems are adaptable to instantaneous heaters.

To make preliminary estimates of hot-water demand when the fixture count is not known, use Table 20 with Figure 36 or Figure 37. The result is usually higher than the demand determined from the actual fixture count. Actual heater size should be determined from Table 19. Hot-water consumption over time can be assumed to be the same as that in the section on Hot-Water Requirements and Storage Equipment Sizing.

Example 11. A 600-student elementary school has the following fixture count: 60 public lavatories, 6 service sinks, 4 kitchen sinks, 6 showers, and 1 dishwasher at 0.5 L/s. Determine the hot-water flow rate for sizing a semi-instantaneous heater based on the following:

a. Estimated number of fixture units

b. Actual fixture count

Solution:

a. Use Table 20 to find the estimated fixture count: 600 students × 0.3 fixture units per student = 180 fixture units. As showers are not included, Table 19 shows 1.5 fixture units per shower × 6 showers = 9 additional fixture units. The basic flow is determined from curve D of Figure 28, which shows that the total flow for 189 fixture units is 1.4 L/s.

b. To size the unit based on actual fixture count and Table 19, the calculation is as follows:

60	public lavatories	×	1.0	FU	=	60 FU
6	service sinks	×	2.5	FU	=	15 FU
4	kitchen sinks	×	0.75	FU	=	3 FU
6	showers	×	1.5	FU	=	9 FU
	Subtotal					87 FU

At 87 fixture units, curve D of Figure 37 shows 1.0 L/s, to which must be added the dishwasher requirement of 0.54 L/s. Thus, the total flow is 1.54 L/s.

Comparing the flow based on actual fixture count to that obtained from the preliminary estimate shows the preliminary estimate to be slightly lower in this case. It is possible that the preliminary estimate could have been as much as twice the final fixture count. To prevent oversizing of equipment, use the actual fixture count method to select the unit.

Special Consideration When Sizing Heat Pump Water Heaters

Heat pump water heaters are potentially attractive water heating options because, when sized and operating correctly, they can exhibit efficiencies of over 300%. Heat pump water heaters (HPWHs), either vapor compression or sorption types, use as part of their energy source external heat extracted from air, water, direct geoexchange, or some other heat source They then use a conventional energy source such as electricity or fossil fuels to upgrade the external source energy in temperature and deliver it to serve hot-water loads. The external source energy is obtained at no extra energy cost, just a capital cost to be able to collect that external source energy, which is why efficiencies are calculated to be greater than 100%. Because HPWH heating rates, power consumption, and efficiency vary substantially with energy source temperature and entering temperature of water to be heated, they are sized in a different manner than conventional systems.

Though it is possible to size HPWH systems to serve the entire annual hot-water load, this may not be the most cost-effective, efficient, or reliable way to design the system. If designers examine the percent utilization of each extra amount of HPWH heating capacity provided above the annual average water heating load, they will find that use of the extra HPWH heating capacity diminishes rapidly as equipment size increases. Moreover number of on-off cycles increases dramatically unless the HPWHs are equipped with variable heat output capacity control (e.g., variable-speed compressors); some are, some are not.

Excessive on-off cycling is not good for equipment reliability and also degrades efficiency because energy invested in the temperature of mass of the HPWH is lost during the off-cycle and must be provided again upon start-up. However, water heating needs must be met, so if the HPWH part of the system is not sized to serve the total annual hot-water load, conventional water heaters of some sort must be provided to carry the remaining hot-water load. It is important to examine system cost-effectiveness when making system design and component sizing decisions. It may be more cost effective to supply a small amount of the annual water heating load using less efficient but less expensive conventional water heaters instead of installing more expensive HPWH capacity that rarely gets used.

HPWH heat source temperature varies greatly with time of day, time of year, and geographic location. Additionally, temperature of the water being heated increases substantially as it is being heated. As a result the heating rates, power consumption and efficiency of HPWHs vary throughout every water heating cycle, and performance of identical HPWH systems will be substantially different in different geographical locations and applications. Proper sizing and performance analysis of HPWH systems requires use of knowledge of how the unit’s heating rate, power consumption, and efficiency vary with heat source temperature and entering water temperature. Reputable HPWH manufactures can provide plots and/or tables of heating rate, power consumption and efficiency (heating rate divided by power consumption) as functions of both water temperature and heat source temperature. In general, heating rate and efficiency increase with lower entering water temperatures and higher heat source temperatures.

Reverse-Rankine-Cycle HPWHS. To date historically most vapor compression HPWHs have used a reverse-Rankine thermodynamic cycle (RRC) where the working fluid (refrigerant) is evaporated on the cold side of the system, compressed, and then condensed on the hot side of the system. Such systems use common refrigerants such as R-134a (and many others). Some RRC HPWH manufacturers offer versions in either conventional (bottom-up/multi-pass) or top-down/single-pass heating configurations. Costs and efficiencies are different for those configurations so water heating system designers should perform cost-effectiveness analyses when making system design and sizing decisions.

Transcritical Cycle HPWHs. Newer HPWHs gaining in popularity use CO_2 as the working fluid and operate on a different thermodynamic cycle called a transcritical cycle, where the refrigerant evaporates in the cold heat exchanger, but when compressed to a high enough pressure and temperature to be useful for heating water, condensation of the refrigerant in the hot heat exchanger is not possible because the temperature and pressure are above the critical point for the refrigerant. Fluids existing at temperatures and pressures above their critical point are so dense that they behave more like liquids than vapors, which is why condensation is not possible. As a result larger hot heat exchangers are required than in reverse-Rankine-cycle HPWH, and thus counter-flow liquid (water) to liquid (supercritical CO_2) heat exchangers are used. To reduce the size of such heat exchangers manufacturers strive to maximize the temperature drop in the supercritical CO_2 and the temperature increase in the water by heating the water from cold to hot in a single pass through the heat exchanger. Thus with CO_2 HPWHs, the water is heated from cold to hot-enough-to-use in a single pass through the heat exchanger. Since storage is normally used with HPWH systems to reduce needed heating rates, the water thus heated must be introduced into the top of storage to avoid wasting its usefulness. Manufacturers of CO_2 HPWHs normally use some sort of water flow rate control through the hot heat exchanger and/or some form of heat pump compressor capacity modulation to control outlet temperature.

Because of differences in the way reverse-Rankine-cycle and transcritical-cycle HPWHs are best operated, they are sized and configured differently. Reverse-Rankine-cycle HPWHs can take advantage of the ability to heat water more efficiency to lower temperatures than to higher temperatures by taking care not to provide excess heating capacity, especially when used in a bottom-up/multi-pass configuration. Remember however that the water heating load must be met, so if the HPWH components are not sized to meet the entire annual water heating load, the remaining needed water heating energy must be provided by a conventional water heater. A cost-effectiveness analysis can help guide design and sizing decisions. In comparison, since CO_2 HPWHs always heat to the desired outlet hot-water use temperature, their capacity and efficiency are less affected by the temperature to which the water is heated: they simply are not designed to heat to temperatures below desired outlet hot-water temperature. A cost-effectiveness analysis is recommended when making and comparing water heating system design and sizing decisions.

HPWH Sizing Calculations. Because of the variable nature of HPWH performance with temperatures, it is best to develop at least simple computer spreadsheet analyses for use in selecting and analyzing performance of HPWH systems. Since a description on how to develop such spreadsheets and use them for HPWH sizing is lengthy, that information is not currently being presented in this chapter. This section simply points out some beneficial factors to consider when sizing heat pump water heater systems. Note that a manufacturer's claimed rated heating capacity and efficiency may not be under a condition that a particular HPWH application is expected to see. Thus it is better to size HPWH equipment using performance curves as opposed to using single-point rated performance values. (Caution: some manufacturer's HPWH systems require the use of water pumps but the manufacturer may not have included the pump power in the energy/power consumption data; this is especially true of equipment manufactured outside the United States. So take care to ensure that the energy consumed to run needed water pumps is included in energy use calculations.)

Since HPWHs are sometimes more expensive per unit of heating capacity than non-HPWHs, to reduce first costs, heat pump water heaters can benefit from a greater ratio of storage tank capacity per unit of energy input than for conventional water heaters.

Optimum cost-effective HPWH system sizing is going to be different for bottom-up/multi-pass HPWHs than for top-down/single-pass HPWH systems. Furthermore, cost-effective HPWH system sizing is also going to be different for HPWHs having single-speed/single-capacity compressors versus HPWHs having variable compressor capacity (e.g., using multiple compressors or variable-speed compressors). It is important to perform cost-effectiveness analysis when designing and sizing HPWH systems, and to include energy use both by the HPWH and conventional water heater (if any) parts of the system. It is also important to include all energy uses (e.g., for making up recirculation-loop and storage heat loss) and not just energy used to heat water delivered to end uses.

As a separate issue from whether or not it is cost effective to let less-efficient but lower-cost conventional water heaters carry part of the annual water heating load, it is usually beneficial to include at least some amount of conventional water heater capacity in HWPH systems. For example, for (hopefully rarely needed) backup when HPWH equipment is undergoing maintenance. There may also be conditions where in some locations and applications the source temperature (e.g., outdoor air) may be too low to let certain HPWHs operate at all (in which case 100% conventional water heater backup is required). Moreover, use of some conventional water heaters may help facilitate more efficient HPWH operation by making up building recirculation-loop heat losses (see Figure 38) so that the HPWHs get to see colder entering water temperatures than if the hot recirculated water is mixed with incoming cold water.

When sizing for redundancy, the HPWH portion of the system can have multiple HPWHs and storage tanks in flow parallel, but when additional conventional water heaters are also provided (normally to help serve peak hot-water loads or provide back-up heating capacity) the cluster of conventional water heaters (which can be in flow parallel with each other) should be in flow series with but downstream of the cluster of HPWHs. Figure 38 shows an example HPWH system plumbing arrangement. Condensing fossil-fired water heaters can also operate more efficiently if configured in this manner, because they receive colder inlet water temperatures. If a hot-water recirculation loop in present, it is important to provide the loop return to the inlet (i.e., upstream of) of the downstream conventional water heaters, but downstream of the heated water provided by the cluster of HPWHs or condensing fossil-fuel water heaters. See the discussion of redundancy earlier in this chapter.

A special note regarding air-source HPWH systems is appropriate. Some brands and/or models of air-source heat pump water heaters will turn off when source air temperature drops, especially below freezing. The above sizing discussions do not address that issue, but if an application is likely to encounter such low source air temperatures, this situation must be considered. In such situations 100% conventional backup heating may be required because the HPWHs may not operate at all.

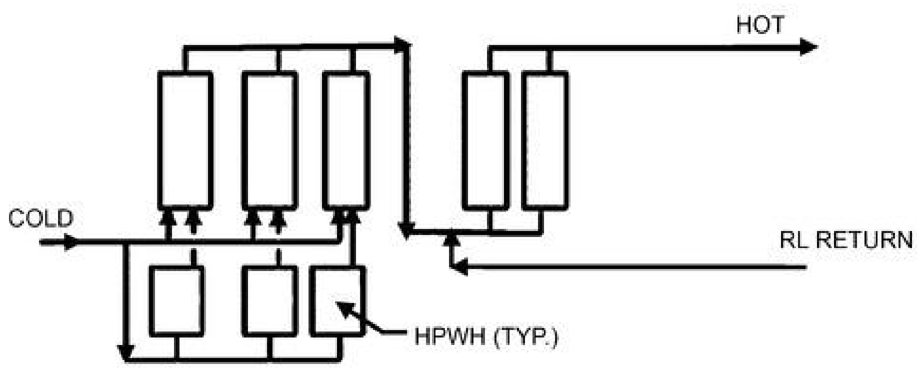

Figure 38. Example Plumbing of HPWH and Conventional Water Heating System

10. WATER-HEATING ENERGY USE

Energy use in water-heating systems includes the following factors, not all of which apply in a given type of system (Hiller 2006c):

- Q_{water} is energy content in water actually used, relative to entering cold-water temperature.
- $Q_{tank\ loss}$ is standby heat loss from water heater storage tank; it is proportional to time and temperature difference between water in tank and surroundings.
- $Q_{cycling\ loss}$ is energy loss from on/off cycling of heat input device, where energy invested in mass of heating device (e.g., heat exchanger) and water in it is lost to surroundings after device turns off; loss is proportional to number of heating cycles (e.g., in a tankless instantaneous water heater). Some fossil-fuel-fired tankless water heaters have pre- and/or postfiring combustion air blower operation to purge combustion products from combustion chamber, which can cause very rapid loss of invested energy in heat exchanger.
- Q_{piping} is heat energy lost from piping while water is flowing; note that, on recirculation-loop systems, heat is lost from both supply and return piping.
- $Q_{cooldown}$ is heat energy lost from piping after flow ceases; note that $Q_{cooldown}$ exhibits a large step increase once water in a pipe cools to below a usable temperature, because remaining warm water in pipe must be dumped to drain before usable hot water can again be obtained at fixtures; time spacing between draws and pipe insulation levels thus strongly influence this energy loss.
- Q_{dump} is energy that must be provided to reheat an amount of water equal to that dumped down the drain while waiting for hot water to arrive at fixtures; knowing the time spacing between draws in nonrecirculated piping systems is very important.
- Input efficiency η_i (tank-type water heater) or thermal efficiency η_t (tankless water heater or heating device external to tank) of heating device must be considered when calculating total water-heating system energy use.
- $Q_{circulating\ pump}$ is energy used to move water within system, if done with pumps. There are often multiple circulating pumps in system (e.g., to circulate water from storage tanks to heating devices, recirculation-loop pumps).
- $Q_{parasitics}$ is energy to operate fans, blowers, controls, and other devices.
- Q_{supply} is energy used to deliver potable water to system and force it through system. Includes pumping energy for well pumps or city water supply pumps, and water treatment system energy.
- $Q_{disposal}$ is energy used to treat and dispose of waste water, including pumping energy and other treatment system energy.

Total piping system energy use is thus

$$Q_{total} = Q_{water}/\eta_i + Q_{tank\ loss}/\eta_i + Q_{cycling\ loss} + Q_{piping}/\eta_i + Q_{cooldown}/\eta_i + Q_{dump}/\eta_i + Q_{circulating\ pump} + Q_{parasitics} + Q_{supply} + Q_{disposal}$$

Additional energy use terms may apply in some water-heating systems.

The following simple examples demonstrate how to compute water-heating system energy use for different system types and draw patterns.

Assumptions for Examples 12 to 15 include the following:

- Two fixtures 30 m apart
- Six 5 min long draws per day of 0.065 L/s, 40°C water at each fixture, spaced 3 min apart compared to 4 h apart
- Water heater output temperature of 50°C
- Tank-type fossil-fuel-fired water heater with input efficiency η_i = 0.80 and a uniform energy factor (UEF) of 0.59, yielding UA_{tank} = 6 W/K, including energy input efficiency (note that tank heat loss rate is a function of UEF rating, not tank size. However, for equal amounts of insulation, smaller tanks have higher UEF rating)
- T_{air} = 20°C for both piping and tank

- T_{cold} = 14.5°C entering cold-water temperature
- Supply piping is 20 mm rigid copper with 13 mm thick foam insulation $(Mc_p)_{w,p,i}$ = 1.58 kJ/(m · K), (from Table 1) pipe volume = 0.3122 L/m
- Return piping is 13 mm rigid copper with 13 mm thick foam insulation (RL system only)
- For simplicity, neglect short lengths of piping between fixture branch piping and main recirculation-loop piping (or tank if at location of fixture)
- For simplicity, neglect supply and disposal energy, recirculating pump energy, and other parasitics.

Example 12. Assume a continuously running hot-water recirculation-loop system with an allowed loop temperature drop to the farthest fixture of 3 K, and assuming one fixture is near the water heater. Note that because this is a continuously running recirculation-loop system, time spacing between draws is unimportant because the supply and return piping are always hot.

Solution: First, compute the recirculation loop flow rate needed to prevent temperature dropping below 47°C, using Equations (1) to (4) and (9).

$$\Delta T_{lm} = \frac{(50-20°C)-(47-20°C)}{\ln[(50-20°C)/(47-20°C)]} = 28.47\ K$$

$$UA_{flowing\ supply} = 0.433\ W/(m{\cdot}K)\ (\text{from Table 1})$$

$$\begin{aligned} Q_{piping\ supply} &= [0.433\ W/(m{\cdot}K)](30\ m)(28.47\ K)/0.8 = 462.28\ W \\ &= (462.28\ J/s)(60\ s/min)(60\ min/h)(24\ h/day) \\ &= 39\ 940\ kJ/day \end{aligned}$$

$$\begin{aligned} m_{circulating\ pump} &= \frac{(462.28\ W)(0.8)}{(1\ kg/L)[4186.8\ J/(kg{\cdot}K)](3\ K)} \\ &= 0.029\ L/s \end{aligned}$$

$$UA_{flowing\ return} = 0.346\ W/(m{\cdot}K)\ (\text{from Table 1})$$

$$\begin{aligned} T_{hot\ return\ out} &= 20°C + (47-20°C)e^{-\left[\frac{[0.346\ W/(m{\cdot}K)](30\ m)}{(0.029\ L/s)(1\ kg/L)[4186.8\ J/(kg{\cdot}K)]}\right]} \\ &= 44.8°C \end{aligned}$$

$$\begin{aligned} Q_{piping\ return} &= (0.029\ L/s)(1\ kg/L)[4.1868\ kJ/(kg{\cdot}K)] \\ &\quad \times (47-44.8°C)/0.8 \\ &= (336\ J/s)(60\ s/min)(60\ min/h)(24\ h/day) \\ &= 28\ 858\ kJ/day \end{aligned}$$

Next, determine the amount of hot water mixed with cold water to deliver the 40°C fixture delivery temperature, from Equation (24).

For the fixture at the water heater,

$$m_{hot\ near} = (0.065\ L/s)(40-14.5°C)/(50-14.5°C) = 0.047\ L/s$$

And for the far fixture,

$$m_{hot\ far} = (0.065\ L/s)(40-14.5°C)/(47-14.5°C) = 0.051\ L/s$$

Consequently,

$$Q_{water\ near} = (0.047\ \text{L/s})(1\ \text{kg/L})[4.1868\ \text{kJ/(kg·K)}](50 - 14.5°\text{C}) \times (60\ \text{s/min})(5\ \text{min/draw})(6\ \text{draws/day})/0.8 = 15\ 692\ \text{kJ/day}$$

$$Q_{water\ far} = (0.051\ \text{L/s})(1\ \text{kg/L})[4.1868\ \text{kJ/(kg·K)}](47 - 14.5°\text{C}) \times (60\ \text{s/min})(5\ \text{min/draw})(6\ \text{draws/day})/0.8 = 15\ 589\ \text{kJ/day}$$

This is the same as for the near fixture, as it should be, because piping heat loss is separately computed.

$$Q_{tank\ heat\ loss} = (6\ \text{W/K})(50 - 20°\text{C})(60\ \text{s/min})(60\ \text{min/h}) \times (24\ \text{h/day}) = 15\ 552\ \text{kJ/day}$$

Thus,

$$Q_{total\ RL\ system} = 39\ 940 + 28\ 858 + 15\ 692 + 15\ 589 + 15\ 552 = 115\ 631\ \text{kJ/day}$$

With the recirculation system, energy use is the same regardless of draw spacing.

Example 13. Assume a nonrecirculated piping system, one fixture at water heater, draws 3 min and 4 h apart.

Solution: First, determine the steady-state delivery temperature at the far fixture, and the actual hot-water flow rate to that fixture. This requires iteration: guessing an initial piping outlet temperature, calculating an estimated hot-water flow rate using Equation (17), and then calculating a new piping outlet temperature based on the calculated flow rate.

Guess $T_{hot\ out\ 1}$ = 50°C. Then,

$$m_{hot\ 1} = \frac{(0.065\ \text{L/s})(40 - 14.5°\text{C})}{(50 - 14.5°\text{C})} = 0.047\ \text{L/s [from Equation (17)]}$$

$$T_{hot\ out\ 2} = 47°\text{C [from Equation (2), where}$$

$$UA_{flowing} = 0.433\ \text{W/(m·K)},\ L = 30\ \text{m]}$$

$$m_{hot\ 2} = \frac{(0.065\ \text{L/s})(40 - 14.5°\text{C})}{(47 - 14.5°\text{C})} = 0.051\ \text{L/s}$$

$$T_{hot\ out\ 3} = 47.1°\text{C}$$

$$m_{hot\ 3} = \frac{(0.065\ \text{L/s})(40 - 14.5°\text{C})}{(47.1 - 14.5°\text{C})} = 0.0508\ \text{L/s}$$

$$T_{hot\ out\ 4} = 47.11°\text{C}$$

Thus,

$$Q_{water\ far} + Q_{piping} = (0.0508\ \text{L/s})(1\ \text{kg/L})[4186.8\ \text{J/(kg·K)}] \times (50 - 14.5°\text{C})(60\ \text{s/min})(5\ \text{min/draw}) \times (6\ \text{draws/day})/0.8 = 16\ 989\ \text{kJ/day}$$

Note that, in this computation, water energy and piping flowing heat loss energy are calculated together for simplicity.

$$Q_{water\ near} = \text{same as in Example 12} = 15\ 692\ \text{kJ/day}$$

Next, compute the pipe temperature at the end of both the 3 min and 4 h cooldown (cd) periods, accounting for the different draw spacing scenarios. For simplicity, base the heat loss calculations on an average pipe temperature of (50 + 47.11°C)/2 = 48.6°C.

Using $UA_{zero\ flow}$ = 0.26 W/(m · K) from Table 1, and Equation (8),

$$\begin{aligned} T_{pipe\ 3\ min} &= 20°C + (48.6 - 20°C)e^{-\left[\frac{[0.26\ W/(m \cdot K)](3\ min)(60\ s/min)}{[1.584\ kJ/(m \cdot K)](1000\ J/kJ)}\right]} \\ &= 47.76°C \end{aligned}$$

and

$$T_{pipe\ 4\ h} = 22.67°C$$

The pipe does not cool below a usable temperature with the 3 min draw spacing, but it does with the 4 h draw spacing. This means that, for the 3 min draw spacing, there are five draws with small amounts of piping cooldown between draws plus one complete cooldown for the last draw of the day, whereas for the 4 h draw spacing, there are six complete cooldowns that result in dumping water in the pipe to drain at the next draw. Because pipe length to the fixture at the water heater is essentially zero under the assumptions here, only draws at the far fixture result in piping energy loses.

From Equation (5)

$$\begin{aligned} Q_{cd\ 3\ min} &= [1584\ J/(m \cdot K)](30\ m)(48.6 - 47.76°C) \\ &\quad \times 5\ cd/day/0.8 + 1\ cd\ (\text{lumped into } Q_{dump}) \\ &= 249.48\ kJ/day \end{aligned}$$

To estimate Q_{dump} and the amount of water waste, assume an AF/PV ratio of 1.5. Thus, each time the pipe cools below a usable temperature, (1.5)(0.3122 L/m)(30 m) = 14.0 L of water must be dumped to drain.

$$\begin{aligned} Q_{dump\ 3\ min} &= (1\ dump/day)(14.0\ L/dump)(1\ kg/L) \\ &\quad \times [4.1868\ kJ/(kg \cdot K)](50 - 14.5°C)/0.8 \\ &= 2601\ kJ/day \end{aligned}$$

$$Q_{dump\ 4\ h} = (6\ dumps/day)(2601\ kJ/dump) = 15\ 606\ kJ/day$$

and

$$Q_{cd\ 4\ h} = 0$$

because all cooldown energy is lumped into Q_{dump}.

$$Q_{tank\ heat\ loss} = 18\ 400\ \text{kJ/day, as in Example 12}$$

To simplify calculation of total water-heating system energy use, it is convenient to add the cooldown energy term computed as shown to the Q_{water} term calculated as if all hot water were delivered to the fixture at a constant flow rate and the steady-state temperature. In reality, the hot-water flow rate to the fixture varies during the initial part of a draw as the cooled but still usable water temperature increases to the steady-state value as flow progresses. The energy use thus computed will be mathematically correct either way.

$$\begin{aligned} Q_{total\ non\text{-}RL,\ 3\ min\ spacing} &= 16\ 989 + 15\ 692 + 248 + 2601 + 18\ 400 \\ &= 53\ 930\ kJ/day \end{aligned}$$

$$\begin{aligned} Q_{total\ non\text{-}RL,\ 4\ h\ spacing} &= 16\ 989 + 15\ 692 + 0 + 15\ 606 + 18\ 400 \\ &= 66\ 687\ kJ/day \end{aligned}$$

Note the large increase in energy use when draws are spaced far enough apart for the pipe to cool to below a usable temperature between draws. Also, the time spent waiting for hot water to arrive at the far fixture is

$$t_{wait} = (14\ \text{L})/(0.065\ \text{L/s}) = 215\ \text{s} = 3.59\ \text{min}$$

Table 21 Results Comparisons for Examples 12 to 15

	3 min Draw Spacing			4 h Draw Spacing		
System Type	**Energy Use, kJ/day**	**Energy Use Compared to One Tank, %**	**Water Waste, L/day**	**Energy Use, kJ/day**	**Energy Use Compared to One Tank, %**	**Water Waste, L/day**
Recirculation loop	118 479	231	0	118 479	184	0
One-tank	53 930	100	14	66 687	100	85.6
Two-tank (large)	68 184	123	0	68 184	98	0
Two-tank (small)	58 341	115	0	58 341	92	0

Example 14. Assume two full-sized water heaters, one at each fixture; no piping.

Solution: In this case, tank heat loss is doubled, but piping heat loss is eliminated.

$$Q_{water} = (2)(15\ 692\ \text{kJ/day}) = 31\ 384\ \text{kJ/day}$$

$$Q_{tank\ heat\ loss} = (2)(18\ 400\ \text{kJ/day}) = 36\ 800\ \text{kJ/day}$$

$$Q_{total\ 2\text{-}tank} = 31\ 384 + 36\ 800 = 68\ 184\ \text{kJ/day}$$

Draw spacing is irrelevant to the two-tank system because there is no piping.

Example 15. Assume two smaller water heaters, one at each fixture; no piping.

Solution: When two separate water heaters are used, each can be smaller than if one water heater were used. Assuming a smaller tank-type fossil-fuel-fired water heater with input efficiency η_i = 0.80 and a UEF of 0.61, yielding UA_{tank} = 5.2 W/K, including energy input efficiency,

$$Q_{water} = (2)(15\ 692\ \text{kJ/day}) = 31\ 384\ \text{kJ/day}$$

$$Q_{tank\ heat\ loss} = (2)(5.2\ \text{W/K})(50 - 20°\text{C})(60\ \text{s/min}) \times (60\ \text{min/h})(24\ \text{h/day}) = 26\ 957\ \text{kJ/day}$$

$$Q_{total\ 2\text{-}tank} = 31\ 384 + 26\ 957 = 58\ 341\ \text{kJ/day}$$

Again, draw spacing is irrelevant to the two-tank system because there is no piping.

Table 21 compares water and energy use of Examples 12 to 15, and shows that the continuously running recirculation-loop system uses substantially more energy than the other approaches (on the order of twice as much). This is not uncommon. Also note that, in these examples, the two-tank approach saves both water waste and energy. The multiple-water-heater approach has at worst only a small negative energy effect if done properly, and under real water draw scenarios usually uses less energy than other options. This is why multiple-water-heater design options should always be considered. In some cases, multiple-water-heater systems can have lower first costs than alternatives. Note that multiple-water-heater systems can use different types of water heaters for different parts of the system: fossil-fuel-fired or heat pump water heaters can be used to serve larger loads, whereas electric resistance water heaters may be preferred for serving smaller loads. In some cases, space limitations, life and maintenance issues, and other factors may make multiple-waterheater systems unattractive.

Both simplified and detailed computer models (Hiller 1992, 2000) are available to help calculate water heater energy use. These are especially useful for analyzing the energy used by heat pump water heaters, where efficiency and heating capacity vary strongly with both source (e.g., air, water) and sink (water) temperature. Computer models are also under development to compute water and energy waste associated with hot-water distribution systems.

11. HEALTH AND SAFETY

Legionellosis (Legionnaires' Disease)

Legionnaires' disease (a form of severe pneumonia) is caused by inhaling aerosolized water droplets containing the bacteria *Legionella pneumophila*. Susceptibility to Legionnaire's disease varies among individuals. People with compromised immune systems (e.g., organ transplant patients or others on immunosuppressant drugs, AIDS patients, smokers, elderly, those with other chronic health conditions or injuries) are at greater risk of contracting the disease at lower exposure levels.

Most water supplied to buildings contains some *Legionella* bacteria (and/or other microorganisms), often at levels too low to detect. The concern is that organism colonies can grow (amplify) within the building hot- and cold-water systems under certain conditions. At *Legionella* concentrations high enough to pose a risk, a hazard may exist. Some examples of conditions potentially conducive to *Legionella* growth are temperatures within a certain range (warm, not too hot or cold), locations of flow stagnation (e.g., pipe dead legs, low flow velocities, other flow stagnation points, intermittent or seasonal use), and inadequate oxidant residual levels. Plumbing design directly impacts variables that can dramatically reduce or increase pathogen growth in the water system. Moreover, water conditioning equipment such as water softeners can experience low flow velocities and high water aging, especially if oversized, which can result in increased pathogen growth in the water system. Both hot- and cold-water temperatures in a water system have an important impact on potential pathogen growth, such as the *Legionella* bacteria, in the water system. For more specific water system design guidance, including discussion of temperature effects, refer to ASHRAE *Standard* 188-2021 and ASHRAE *Guideline* 12-2020.

Scalding

Scalding is an important concern in design and operation of potable hot-water systems. Figure 39 (Moritz 1947) shows plots of exposure time versus water temperature that results in both first-degree (pain, redness, swelling, minor tissue damage) and full-thickness third-degree (permanent damage, scarring) skin burns in adults. Children burn even more rapidly. Note that, at the high temperatures required for some commercial and institutional operations (e.g., 140°F60°C and above), burns can occur almost instantaneously (3 s or less exposure). Even at lower temperatures such as 124°F51°C, found commonly in multifamily housing, hospitality, and light commercial facilities, burns can occur in 2 min. Safety dictates some trade-offs to limit scalding injuries (e.g., during pressure transients that may inhibit proper operation of temperature regulating valves) while minimizing risk of Legionnaire’s disease.

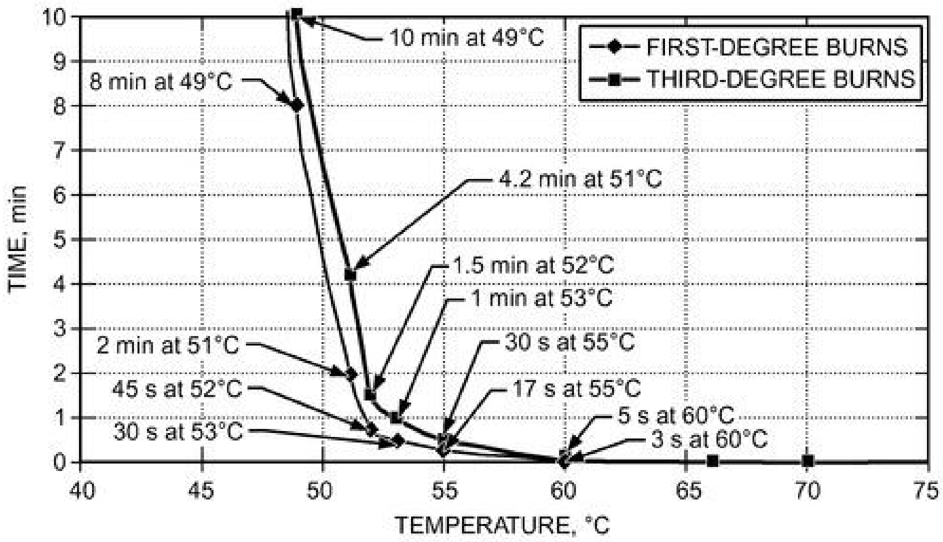

Figure 39. Time for Adult Skin Burns in Hot Water

Temperature Requirement

Typical temperature guidelines for some services are shown in Table 22. A 60°C water temperature minimizes flue gas condensation in the equipment.

Other Safety Concerns

Regulatory agencies differ as to the selection of protective devices and methods of installation. It is therefore essential to check and comply with the manufacturer’s instructions and the applicable local codes. In the absence of such instructions and codes, the following recommendations may be used as a guide:

- Water expands when it is heated. Although the water-heating system is initially under service pressure, the pressure rises rapidly if backflow is prevented by devices such as a check valve, pressure-reducing valve, or backflow preventer in the cold-water line or by temporarily shutting off the cold-water valve. When backflow is prevented, the pressure rise during heating may cause the safety relief valve to weep to relieve the pressure. However, if the safety relief valve is inadequate, inoperative, or missing, pressure rise may rupture the tank or cause other damage. Systems having this potential problem must be protected by a properly sized expansion tank located on the cold-water line downstream of and as close as practical to the device preventing backflow.
- Temperature-limiting devices (energy cutoff/high limit) prevent water temperatures from exceeding 99°C by stopping the flow of fuel or energy. These devices should be listed and labeled by a recognized certifying agency.
- Safety relief valves open when pressure exceeds the valve setting. These valves are typically applied to water-heating and hot-water supply boilers. The set pressure should not exceed the maximum allowable working pressure of the boiler. The

heat input pressure steam rating (in kW) should equal or exceed the maximum output rating for the boiler. The valves should comply with current applicable standards or the ASME *Boiler and Pressure Vessel Code*.

- Temperature and pressure safety relief valves also open if the water temperature reaches 99°C. These valves are typically applied to water heaters and hot-water storage tanks. The heat input temperature/steam rating (in kW) should equal or exceed the heat input rating of the water heater. Combination temperature- and pressure-relief valves should be installed with the temperature-sensitive element located in the top 150 mm of the tank (i.e., where the water is hottest).
- To reduce scald hazards, discharge temperature at fixtures accessible to the occupant should not exceed 50°C. Thermostatically controlled mixing valves can be used to blend hot and cold water to maintain safe service hot-water temperatures.
- A relief valve should be installed in any part of the system containing a heat input device that can be isolated by valves. The heat input device may be solar water-heating panels, desuperheater water heaters, heat recovery devices, or similar equipment.

Table 22 Representative Hot-Water Temperatures

Use	Temperature, °C
Lavatory	
Hand washing	40
Shaving	45
Showers and tubs	43
Therapeutic baths	35
Commercial or institutional laundry, based on fabric	up to 82
Residential dish washing and laundry	60
Surgical scrubbing	43
Commercial spray-type dish washing[a]	
Single- or multiple-tank hood or rack type	
Wash	65 minimum
Final rinse	82 to 90
Single-tank conveyor type	
Wash	71 minimum
Final rinse	82 to 90
Single-tank rack or door type	
Single-temperature wash and rinse	74 minimum
Chemical sanitizing types[b]	60
Multiple-tank conveyor type	
Wash	65 minimum
Pumped rinse	71 minimum
Final rinse	82 to 90
Chemical sanitizing glass washer	
Wash	60
Rinse	24 minimum

[a] As required by NSF.

[b] See manufacturer for actual temperature required.

12. WATER QUALITY, SCALE, AND CORROSION

A complete water analysis and an understanding of system requirements are needed to protect water-heating systems from scale and corrosion. Analysis shows whether water is hard or soft. Hard water, unless treated, causes scaling or liming of heat transfer and water storage surfaces; soft water may aggravate corrosion problems and sacrificial anode consumption (Talbert et al. 1986). Water treatment (e.g., water softeners) can have a detrimental impact on water heater equipment life, by causing accelerated anode rod deterioration and increased storage tank corrosion rates. Consult water heater manufacturers' literature for guidance on acceptable water treatment options.

Scale formation is also affected by system requirements and equipment. As shown in Figure 40, the rate of scaling increases with temperature and use because calcium carbonate and other scaling compounds lose solubility at higher temperatures. In water tube-type equipment, scaling problems can be offset by increasing water velocity over the heat transfer surfaces, which reduces the tube surface temperature. Also, flow turbulence, if high enough, works to keep any scale that does precipitate off the surface. When water hardness is over 140 mg/L, water softening or other water treatment is often recommended. Consult manufacturers' recommendations.

Corrosion problems increase with temperature because corrosive oxygen and carbon dioxide gases are released from the water. Electrical conductivity also increases with temperature, enhancing electrochemical reactions such as rusting (Taborek et al. 1972). A deposit of scale provides some protection from corrosion; however, this deposit also reduces the heat transfer rate, and it is not under the control of the system designer (Talbert et al. 1986).

Steel vessels can be protected to varying degrees by galvanizing or by lining with copper, glass, cement, electroless nickel-phosphorus, or other corrosion-resistant material. Glass-lined vessels are almost always supplied with electrochemical protection. Typically, one or more anode rods of magnesium, aluminum, or zinc alloy are installed in the vessel by the manufacturer. This electrochemically active material sacrifices itself to reduce or prevent corrosion of the tank (the cathode). Higher temperature, softened water, and high water use may lead to rapid anode consumption. Manufacturers recommend periodic replacement of the anode rod(s) to prolong the life of the vessel. Some waters have very little electrochemical activity. In this instance, a standard anode shows little or no activity, and the vessel is not adequately protected. If this condition is suspected, consult the equipment manufacturer on the possible need for a high-potential anode, or consider using vessels made of nonferrous material.

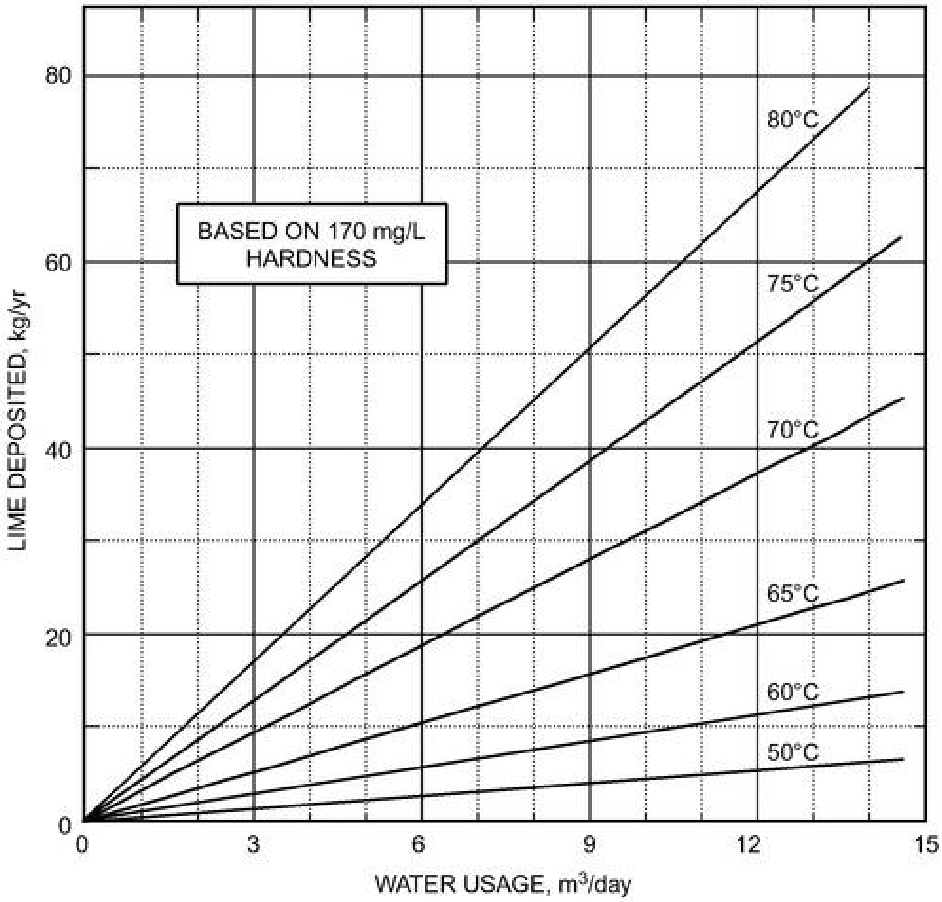

Figure 40. Lime Deposited Versus Temperature and Water Use (Based on data from Purdue University *Bulletin* No. 74)

Water heaters and hot-water storage tanks constructed of stainless steel, copper, or other nonferrous alloys are protected against oxygen corrosion. However, care must still be taken, as some stainless steel may be adversely affected by chlorides, and copper may be attacked by ammonia or carbon dioxide.

Water treatment systems (e.g., water softeners) can sometimes not only produce conditions detrimental to water heating equipment life, but they can also have less-than-desirable environmental impacts. Avoiding water treatment system oversizing and sizing to produce more thoroughly treated water than necessary both reduce production of less-desirable effluents, and can reduce idle times that result in flow stagnation and thus can exacerbate biological growth.

13. SPECIAL CONCERNS

Cross Flow at End-Use Fixtures

Cross flow occurs when there is a connection between the hot- and cold-water lines. Cross flow is problematic because moving hot water into the cold line or, alternatively, moving cold water into the hot line, can affect the performance of end-use equipment, reduce hot-water outlet temperatures or mix hot water into the cold line used for drinking water or ice making. If not resolved, cross flow in facilities can cause energy and water waste, poor water system performance, and facilitate growth of *Legionella*.

One way to determine whether cross flow is occurring from the cold-water side is to turn off the valve on the water heater cold-water inlet and let only hot water flow at a faucet. If pressure drops and water ceases to flow, then there is no cross flow, but if water continues to flow, this indicates cross flow between the hot and cold lines in the system.

Cross flow can occur in the commercial setting at various locations on the water distribution system, including at mop or utility sink faucets and at prerinse spray valve faucets. These are locations where both the hot- and cold-water valves are commonly kept in the open position for downstream tempering of water for “on-demand” sanitation tasks. Assemblies such as in-line chemical dispensers, hoses with attached spray nozzles, or downstream shutoff valves installed for filling mop buckets may promote cross flow if check valves are not installed. Similarly, in commercial kitchens, prerinse spray valve operation typically requires leaving the hot- and cold-water valves open at the faucet in advance of spray valve operation. Another place where cross flow can occur is with single-handle faucets at hand sinks and showers, where a worn seal in the faucet can cause a direct connection of the cold and hot line.

Installing a check valve on both the hot-water and cold-water connections at end-use fixtures ensures that water only flows in a single direction, eliminating cross flow. To ensure that cross flow at the faucet is prevented, specify faucets with check valves included. Otherwise, check valves should be installed ahead of these faucets on both the hot and cold lines.

Hot Water from Tanks and Storage Systems

With storage systems, 60 to 80% of the hot water in a tank is assumed to be usable before dilution by cold water lowers the temperature below an acceptable level. However, better designs can exceed 90%. Thus, the maximum hot water available from a self-contained storage heater is usually

$$V_t = Rd + MS_t \qquad (18)$$

where

V_t	=	available hot water, L
R	=	recovery rate at required temperature, L/s
d	=	duration of peak hot-water demand, s
M	=	ratio of usable water to storage tank capacity
S_t	=	storage capacity of heater tank, L

However, Equation (18) only applies if the water draw rate is less than the available reheat rate. Otherwise, the tank cannot heat the flowing water to a usable temperature during the draw, and V_t drops to the same as an unfired tank. For example, a fossil-fuel-fired heater with a fuel input rate of 13 kW and an input efficiency of 80% can raise the temperature of water being drawn through a storage tank at a rate of 200 mL/s by approximately 13 K. If the entering cold-water temperature is 16°C, the water will be heated to only 28°C, too cold to be useful, so the heating rate cannot contribute to effective storage tank capacity under a prolonged draw at this flow rate. In reality, draw rates are rarely constant during peak draw or other times. Computer simulation models allow equipment sizing under these more realistic conditions (Hiller 1992).

Maximum usable hot water from an unfired tank is

$$V_a = MS_a \qquad (19)$$

where

V_a	=	usable water available from the unfired tank, L
S_a	=	capacity of the unfired tank, L

Note: Assumes tank water at required temperature.

Hot water obtained from a water heater using a storage heater with an auxiliary storage tank is

$$V_z = V_t + V_a \qquad (20)$$

where V_z is total hot water available during one peak, in litres.

Placement of Water Heaters

Many types of water heaters may be expected to leak at the end of their useful life. They should be placed where leakage will not cause damage. Alternatively, suitable drain pans piped to drains must be provided.

Water heaters not requiring combustion air may generally be placed in any suitable location, as long as relief valve discharge pipes open to a safe location.

Water heaters requiring ambient combustion air must be located in areas with air openings large enough to admit the required combustion/dilution air (see NFPA *Standard* 54/ANSI Z223.1).

For water heaters located in areas where flammable vapors are likely to be present, precautions should be taken against ignition. For water heaters installed in residential garages, additional precautions should be taken. Consult local codes for additional requirements or see sections 5.1.9 through 5.1.12 of NFPA *Standard* 54/ANSI Z223.1.

Outdoor models with a weather-proofed jacket are available. Direct-vent gas- and oil-fired models are also available; they are to be installed inside, but are not vented through a conventional chimney or gas vent. They use outdoor air for combustion. They must be installed with the means specified by the manufacturer for venting (typically horizontal) and for supplying air for combustion from outside the building.

Air-source heat pump water heaters require access to an adequate air supply from which heat can be extracted. For residential units, a room of at least 27 m^3 or ducted air is recommended. See manufacturer's literature for more information.

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