

CHAPTER 50

SERVICE WATER HEATING

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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 Some of the data in this chapter on hot-water demands for some types of buildings, applications, and fixtures may be outdated.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, washdown 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.

First-hour rating. An indicator of the maximum amount of hot water a residential water heater can supply in 1 h. This rating is used by the Federal Trade Commission (FTC) for comparative purposes. 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.

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 12 in. 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**.

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

The preparation of this chapter is assigned to TC 6.6, Service Water Heating Systems.

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 gallons 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 Btu/h energy consumption required to maintain any water/air temperature difference by taking the percent times the temperature difference, times 8.25 Btu/gal·°F (a nominal specific heat for water), times the tank capacity, and then dividing by 100.

Standby loss coefficient. The heat input (in Btu/h·°F) 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).

3. SYSTEM PLANNING

The goals of system planning are to (1) size the system properly; (2) optimize system efficiency; and (3) minimize first, operating, and overall life-cycle costs. 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.

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, 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 energy factors.
- 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.

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, is an effective thought process to achieve higher system efficiency and performance.

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.

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.

5. END-USE FIXTURES

Advanced end-use fixtures 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, achieves 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 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 0.5 gpm for public hand sinks and 2.2 gpm for private hand sinks. Manufacturers are now making public sink faucet aerators that flow as low as 0.35 gpm and private sink faucet aerators that use 1.5 gpm. Similarly, manufacturers are now producing showerheads that use 2.0 gpm, reduced from the federally mandated 2.5 gpm flow rate.

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 1.6 gpm (DOE 2011), reduced from conventional models rated at 2.5 to 4.5 gpm. Spray valves flowing at 0.65 to 1.28 gpm 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; this may 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 140 and 180°F 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 2009 *ASHRAE Handbook—Fundamentals*). 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.

Supply Piping

Table 16, Figures 27 and 28, 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 2009 *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

Sizing both cold- and hot-water piping requires that the pressure differential at the point of use of blended hot and cold water be kept to a minimum. This is particularly important for tubs and showers, because sudden changes in flow at fixtures cause discomfort and a possible scalding hazard. Pressure-compensating devices are available.

Effect of Distribution Design on Efficiency of Condensing Heaters

The distribution system design and operation can have a significant impact on the efficiency of gas-fired condensing 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 1 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

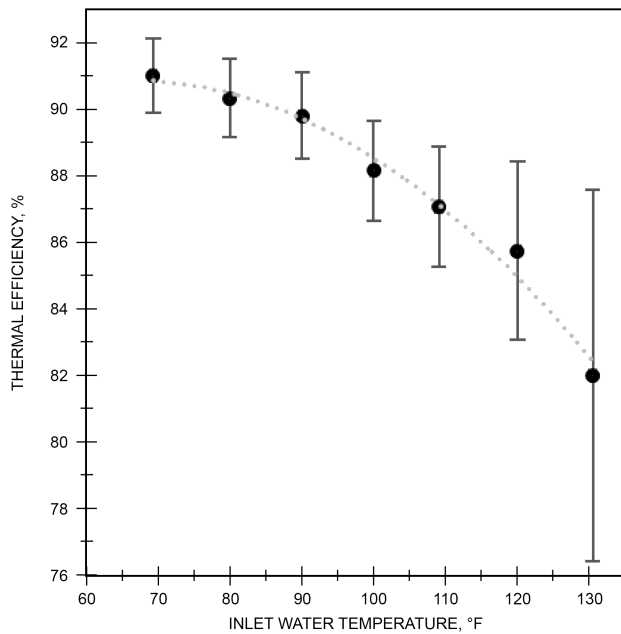


Fig. 1 Effect of Inlet Water Temperature on Thermal Efficiency of Condensing Tankless Heater

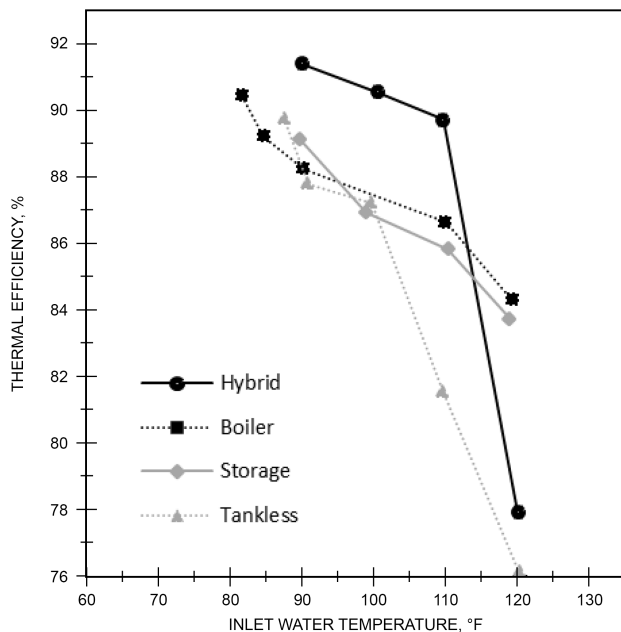


Fig. 2 Effect of Return Water Temperature on Operating Efficiency of Condensing Heaters

devices (Huestis 2013; Johnson et al. 2013). The unit loses all condensing function at inlet temperatures of 130°F, where the thermal efficiency reaches 82%, typical of a standard-efficiency unit.

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 2) with an outlet temperature of 130°F at 3 gpm 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 55 gal and boiler with a flooded volume of less than 3.7 gal demonstrated a steady decline in efficiency from approximately 90% thermal efficiency at 90°F to 84% efficiency at 120°F (partially condensing). For the hybrid heater with a storage volume of 2 gal, the unit maintained condensing function with an average efficiency of 90% with a return water temperature from 90 to 110°F, but then the efficiency rapidly dropped to 78% at 120°F return water temperature. The tankless heater performed the worst, with a large drop in operating efficiency from 90% at 87°F to 76% efficiency at 120°F. Both the hybrid and tankless units lost the ability to capture latent heat from the exhaust gases at 120°F. Finding alternatives to the use of continuous recirculation systems, or maintaining a return temperature at 100°F or lower, would significantly improve the efficiency of condensing water heaters.

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* series 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 3/4 in. 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 3/4 in. foam reduces plastic pipe heat loss rates to

Table 1 Piping Heat Loss Factors for Foam In Piping
Heat Loss Factors for Foam Insulation with Thermal
Conductivity of 0.02 Btu/h·ft²·°F

Nominal Pipe Size	Foam Insulation Thickness, in.	$UA_{zero\ flow}$, Btu/h·ft·°F	High-Value $UA_{flowing}$, Btu/h·ft·°F
1/2 in. rigid copper	0	0.226	0.36
	0.5	0.128	0.20
	0.75	0.116	0.19
3/4 in. rigid copper	0	0.388	0.44
	0.5	0.150	0.25
	0.75	0.142	0.24
3/4 in. rolled copper	0	0.334	0.334
	0.75	0.138	0.16
3/4 in. roll CU-sand	0	1.2	2.82
	0.75	0.155	0.177
3/4 in. PEX-AL-PEX ^a	0	0.550	0.546
	0.5	0.199	0.199
	0.75	0.158	0.18
3/4 in. PEX ^b	0	0.535	0.585
	0.75	0.159	0.19
1/2 in. PEX	0	0.438	0.438
	0.75	0.13	0.13
3/8 in. PEX	0		
3/4 in. CPVC	0	0.44	0.52
	0.75	0.148	0.17

Note: Results are for horizontal in-air tests unless otherwise noted.

Sources: Hiller (2005a, 2005b, 2006b, 2008, 2009).

^aHigh-density cross-linked polyethylene, aluminum, high-density cross-linked polyethylene multilayer pipe.

^bHigh-density cross-linked polyethylene.

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).

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:

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

where

ΔT_{lm} = log mean temperature difference, °F

Q = heat loss rate, Btu/h

m = water flow rate, lb_m/h

c_p = specific heat of water, 1 Btu/lb_m·°F

$T_{hot\ in}$ = water temperature entering pipe, °F

$T_{hot\ out}$ = water temperature leaving pipe, °F

$UA_{flowing}$ = flowing heat loss factor per foot of pipe, Btu/h·ft·°F

L_{pipe} = length of hot-water pipe, ft

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

Under zero-flow cooldown conditions,

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

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

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

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

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

where

t_1 = initial time

t_2 = final time

Q = average heat loss rate from time t_1 to time t_2 , Btu/h·ft

$(Mc_p)_{w,p,i}$ = sum of mass times specific heat for water, pipe, and insulation, Btu/ft·°F

$T_{hot\ t_1}$ = pipe temperature at t_1 , °F

$T_{hot\ t_2}$ = pipe temperature at t_2 , °F

$UA_{zero-flow}$ = zero-flow heat loss factor per foot of pipe, Btu/h·ft·°F

Note that the quantity $(UA_{zero-flow})(t_2 - t_1)/(Mc_p)_{w,p,i}$ must be non-dimensional, 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

Table 2 Approximate Heat Loss from Piping at 140°F Inlet, 70°F Ambient

Nominal Size, in.	Bare Copper Tubing, Btu/h·ft	Bare Copper UA, Btu/h·ft·°F	0.5 in. Glass Fiber Insulated Copper Tubing, Btu/h·ft	0.5 in. Glass Fiber Insulated Copper UA, Btu/h·ft·°F
0.75	30	0.43	17.7	0.25
1	38	0.54	20.3	0.29
1.25	45	0.64	23.4	0.33
1.5	53	0.76	25.4	0.36
2	66	0.94	29.6	0.42
2.5	80	1.14	33.8	0.48
3	94	1.34	39.5	0.56
4	120	1.71	48.4	0.69

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 105°F 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 11 to 14 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.

For small installations, a simplified pump sizing method is to allow 1 gpm for every 20 fixture units in the system, or to allow 0.5 gpm for each 3/4 or 1 in. riser; 1 gpm for each 1 1/4 or 1 1/2 in. riser; and 2 gpm for each riser 2 in. 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 Btu/h·ft or uninsulated pipe by 60 Btu/h·ft. [Table 2](#) gives actual heat losses in pipes at a service water temperature of 140°F and ambient temperature of 70°F. The values of 30 or 60 Btu/h·ft are only recommended for ease in calculation.

3. Determine pump capacity as follows:

$$Q_p = \frac{q}{60\rho c_p \Delta t} \quad (9)$$

where

Q_p = pump capacity, gpm

q = heat loss, Btu/h

ρ = density of water = 8.25 lb/gal (120°F)

c_p = specific heat of water = 1 Btu/lb·°F

Δt = allowable temperature drop, °F

For a 20°F allowable temperature drop,

$$Q_p(\text{gpm}) = \frac{q}{60 \times 8.25 \times 1 \times 20} = \frac{q}{9900} \quad (10)$$

Caution: This calculation assumes that a 20°F 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. Multiply the head by 100 and divide by the total length of hot water return piping to determine the allowable friction loss per 100 ft 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. A swing-type check valve should be placed in each 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 3](#). 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.

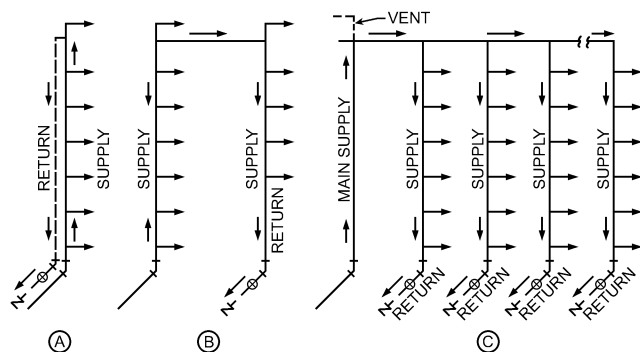


Fig. 3 Arrangements of Hot-Water Circulation Lines

Generally, for small installations, a nominal pipe size (NPS) 1/2 or 3/4 in. 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*.

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 30 to 60 ft (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 15 psig minimum, 25 psig maximum, and 20 psig 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 15 psig, a booster pump or other means should be installed to provide supply water at 20 psig.

Flow pressure over 25 psig causes atomization of the 180°F rinse water, resulting in excessive temperature drop (which can be as much as 15°F 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).

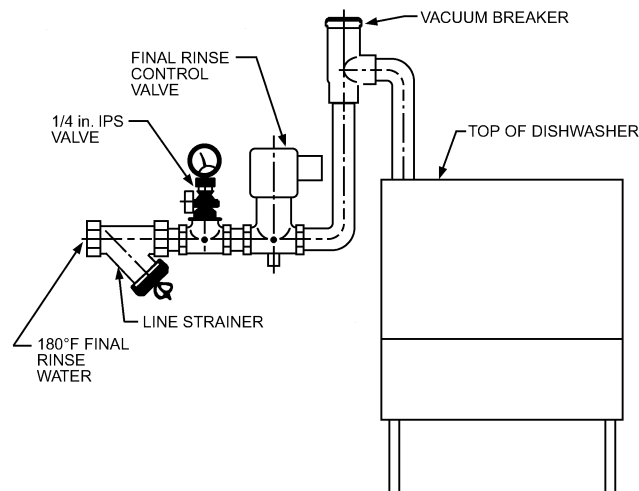


Fig. 4 National Sanitation Foundation (NSF) Plumbing Requirements for Commercial Dishwasher

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 1.
- The supply line that carries 180°F water from the water heater to the dishwasher should not be smaller than NPS 3/4.
- No auxiliary feed lines should connect to the 180°F supply line.
- A return line should be installed if the source of 180°F water is more than 5 ft 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 60 ft, 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 1/4 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 4).
- 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 5). Applicable codes should be consulted for mixing valve requirements.

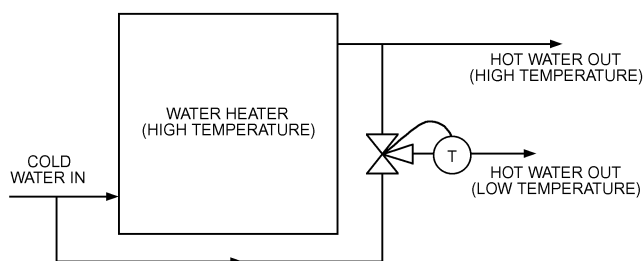


Fig. 5 Two-Temperature Service with Mixing Valve

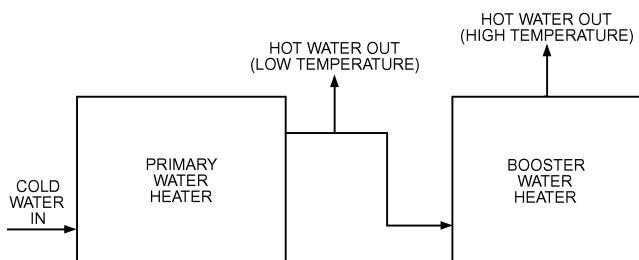


Fig. 6 Two-Temperature Service with Primary Heater and Booster Heater in Series

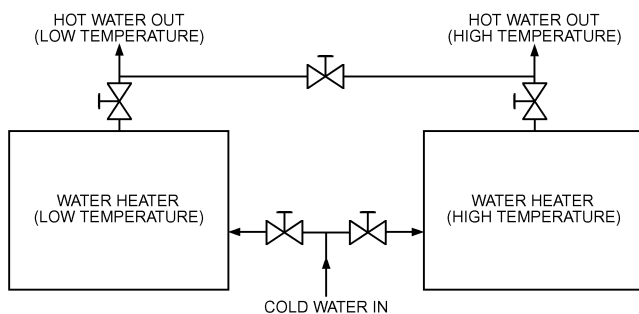


Fig. 7 Two-Temperature Service with Separate Heater for Each Service

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 6). This method offers better protection against scalding.

A third method uses separate heaters for the higher-temperature service (Figure 7). 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.

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.

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 8). The unit having its inlet closest to the cold-water supply is piped so that its outlet is farthest from the hot-water

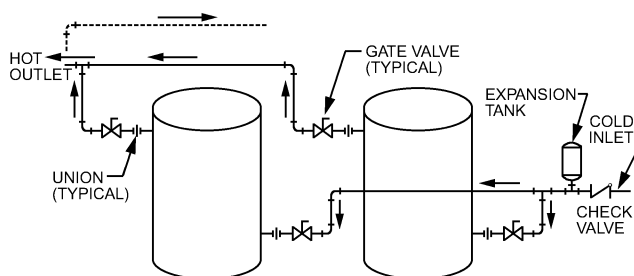


Fig. 8 Reverse/Return Manifold System

supply line. Quite often this results in a hot-water supply line that reverses direction (see dashed line, Figure 8) to bring it back to the first unit in line; hence the name reverse/return.

7. WATER-HEATING EQUIPMENT

Gas-Fired Systems

Storage water heaters incorporate the burner(s), storage tank, outer jacket, and controls such as a thermostat in a single unit and typically have an input-to-storage capacity ratio of less than 4000 Btu/h per gallon.

Instantaneous water heaters are produced in two distinctly different types. Tank-type instantaneous heaters have an input-to-storage capacity ratio of 4000 Btu/h per gallon or more and a thermostat to control energy input to the heater. Water-tube instantaneous heaters have minimal water storage capacity. They usually have a flow switch that controls the burner, and may have a modulating fuel valve that varies fuel flow as water flow changes.

Tankless water heaters have almost no storage capacity, and heat water as it flows once through the water heater. Heating rate required varies with water flow rate and needed temperature rise. They are best suited for steady-state operation. 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 gas 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/tankless and (4) 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 50 gal or less with an input rating of 105,000 Btu/h 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

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 120 gal 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 the 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. 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 38 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 15). 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.

Heat pump water heaters (HPWHs) use a vapor-compression 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” water heater, which is connected to a separately specified storage water tank, the size of which is generally dependent upon the application requirements. Most HPWHs can generate hot-water temperatures up to 140°F, with some models capable of outlet temperatures in the 180°F 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 source temperature is warm. HPWHs frequently require additional storage tank capacity above normal for the application because they have lower recovery rates than standard water heaters. This excludes their application in facilities where space is limited or at a premium. A benefit of larger storage tanks is that it allows for the use of smaller-capacity HPWHs with higher run times to meet the hot water demand, often reducing the total system cost. Despite the limitations of HPWHs, their ability to produce heat from one unit of energy is two to three times higher than standard resistance and fossil-fueled water heaters. Larger storage water capacity allows the use of smaller capacity HPWHs, often reducing the total system cost. As an air-source HPWH collects heat, it provides a potentially useful cooling effect and also dehumidifies the air. The effect of an air-source HPWH cooling output on the building's energy balance should be considered. Cooling output should be directed to provide occupant comfort 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 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 9). 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.

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 35 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

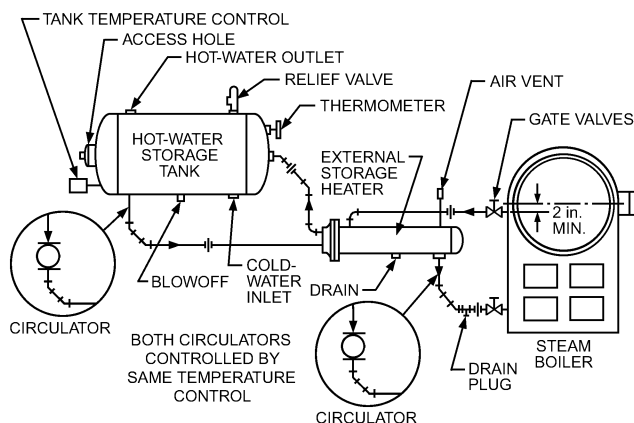


Fig. 9 Indirect, External Storage Water Heater

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.

9. HOT-WATER LOAD AND EQUIPMENT SIZING

Methods for sizing storage water heaters vary. Those using recovery versus storage curves are based on extensive research. All methods provide adequate hot water if the designer allows for unusual conditions. To serve a hot-water load adequately, the needs of both the peak energy withdrawal rate and total integrated energy delivery for end uses must be met. Meeting these needs can be done either by providing a heating rate large enough to meet the peak energy withdrawal rate of the system (and modulating that heating input for smaller loads), or by providing a lower heating rate combined with storage (from which the peak rates can be satisfied). Lower costs are usually achieved by using at least some storage. A variety of different heating rate/storage volume combinations can be used to meet the needs of a given water-heating load profile (Hiller 1998).

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.

Some of the 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 load that is ever actually used 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; it remains, however, the best information currently available (with a few exceptions, as noted). Of greatest 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; Goldner 1994a, 1994b; Goldner and Price 1999; Hiller 1998; Hiller and Lowenstein 1996, 1998; Thrasher and DeWerth 1994), but much more information in a variety of applications is needed before the design procedures can be updated. 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 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.

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

Table 3 Typical Residential Use of Hot Water

Use	High Flow, Gallons/Task	Low Flow (Water Savers Used), Gallons/Task	Ultralow Flow, Gallons/Task
Food preparation	5	3	3
Hand dish washing	4	4	3
Automatic dishwasher	15	15	3 to 10
Clothes washer	32	21	5 to 15
Shower or bath	20	15	10 to 15
Face and hand washing	4	2	1 to 2

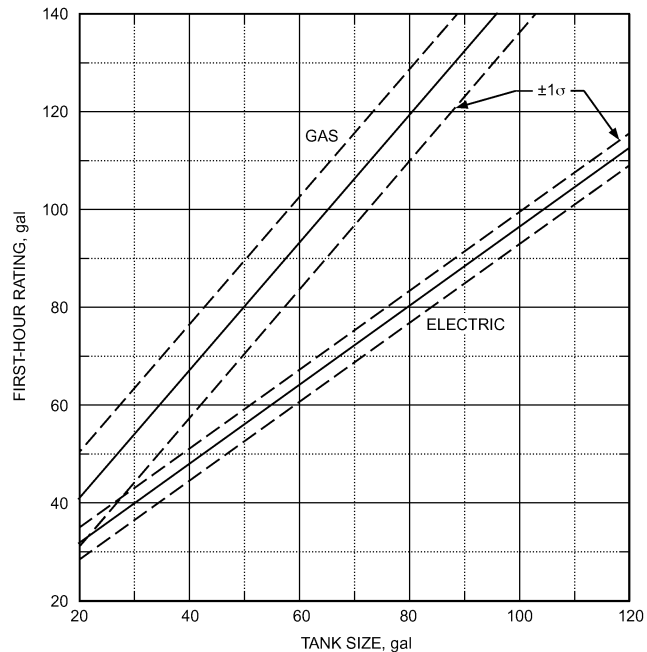


Fig. 10 First-Hour Rating (FHR) Relationships for Residential Water Heaters

some automatically adjust the amount of hot water they use based on sensed load or cycle setting. 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.

The first-hour rating (FHR) is the theoretical maximum amount of hot water that the water heater can supply in 1 h of operation under specific test conditions (DOE 1998). The linear regression lines shown in Figure 10 represent the FHR for 1556 electric heaters and 2901 gas heaters [GAMA (Continuous Maintenance); Hiller 1998]. Regression lines are not included for oil-fired and heat-pump water 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 first-hour rating for residential applications.

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

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

Number of Baths Number of Bedrooms	1 to 1.5			2 to 2.5				3 to 3.5			
	1	2	3	2	3	4	5	3	4	5	6
Gas^a											
Storage, gal	20	30	30	30	40	40	50	40	50	50	50
1000 Btu/h input	27	36	36	36	36	38	47	38	38	47	50
1 h draw, gal	43	60	60	60	70	72	90	72	82	90	92
Recovery, gph	23	30	30	30	30	32	40	32	32	40	42
Electric^a											
Storage, gal	20	30	40	40	50	50	66	50	66	66	80
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, gal	30	44	58	58	72	72	88	72	88	88	102
Recovery, gph	10	14	18	18	22	22	22	22	22	22	22
Oil^a											
Storage, gal	30	30	30	30	30	30	30	30	30	30	30
1000 Btu/h input	70	70	70	70	70	70	70	70	70	70	70
1 h draw, gal	89	89	89	89	89	89	89	89	89	89	89
Recovery, gph	59	59	59	59	59	59	59	59	59	59	59
Tank-type indirect^{b,c}											
I-W-H-rated draw, gal in 3 h, 100°F rise		40	40		66	66 ^e	66	66	66	66	66
Manufacturer-rated draw, gal in 3 h, 100°F rise		49	49		75	75 ^e	75	75	75	75	75
Tank capacity, gal		66	66		66	66 ^e	82	66	82	82	82
Tankless-type indirect^{c,d}											
I-W-H-rated draw, gpm, 100°F rise		2.75	2.75		3.25	3.25 ^e	3.75	3.25	3.75	3.75	3.75
Manufacturer-rated draw, gal in 5 min, 100°F rise		15	15		25	25 ^e	35	25	35	35	35

Note: Applies to tank-type water heaters only.

^aStorage 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.

^bBoiler-connected water heater capacities (180°F boiler water, internal or external connection).

^cHeater capacities and inputs are minimum allowable. Variations in tank size are permitted when recovery is based on 4 gph/kW at 100°F rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot-water heaters.

^dBoiler-connected heater capacities (200°F boiler water, internal or external connection).

^eAlso for 1 to 1.5 baths and 4 bedrooms for indirect water heaters.

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

Group	Average Hot-Water Use, gal							
	Hourly		Daily		Weekly		Monthly	
	OVL	Peak	OVL	Peak	OVL	Peak	OVL	Peak
All families	2.6	4.6	62.4	67.1	436	495	1897	2034
"Typical" families	2.6	5.8	63.1	66.6	442	528	1921	2078

point be approximately 120°F 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.

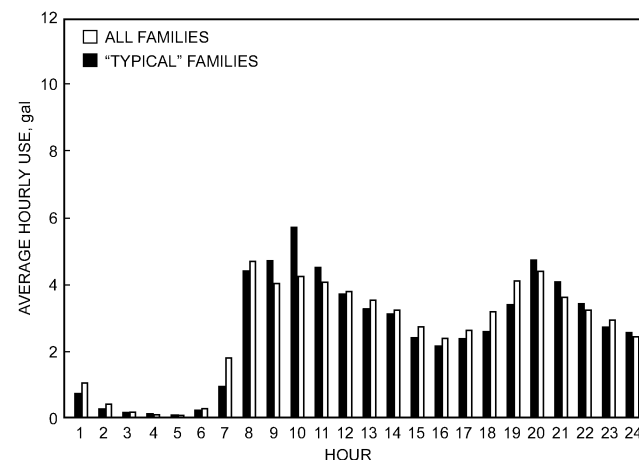
The structure and lifestyle of a typical family (variations in family size, age of family members, presence and age of children, hot-water use volume and temperature, and other factors) cause hot-water consumption demand patterns to fluctuate widely in both magnitude and time distribution.

Pertman 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 illustrated in Figures 11 and 12. Samples of results from the analysis of similarities in hot-water use are given in Figures 13 and 14.

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 (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

**Fig. 11 Residential Average Hourly Hot-Water Use**

motels 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.

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

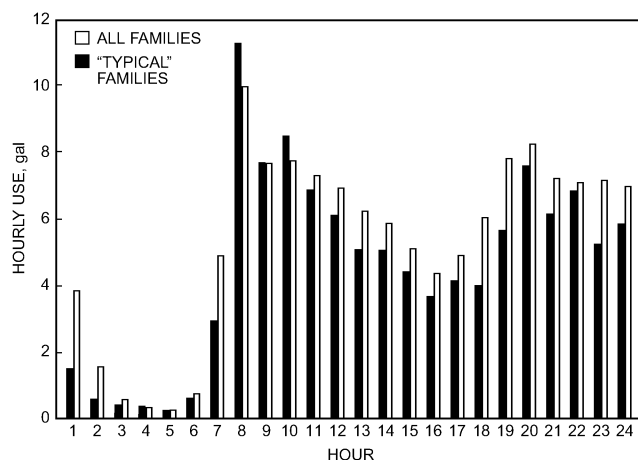


Fig. 12 Residential Hourly Hot-Water Use, 95% Confidence Level

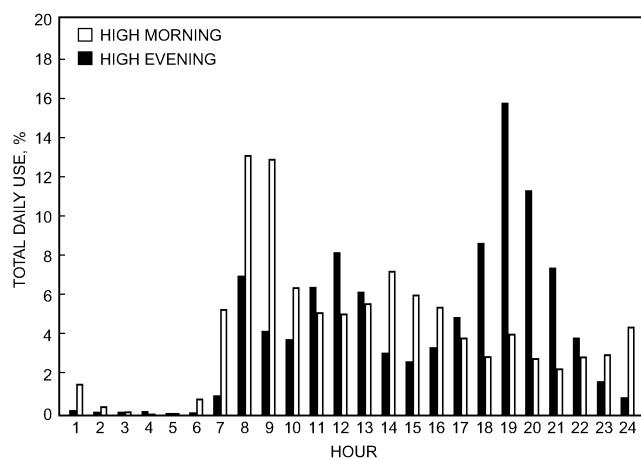


Fig. 13 Residential Hourly Hot-Water Use Pattern for Selected High Morning and High Evening Users

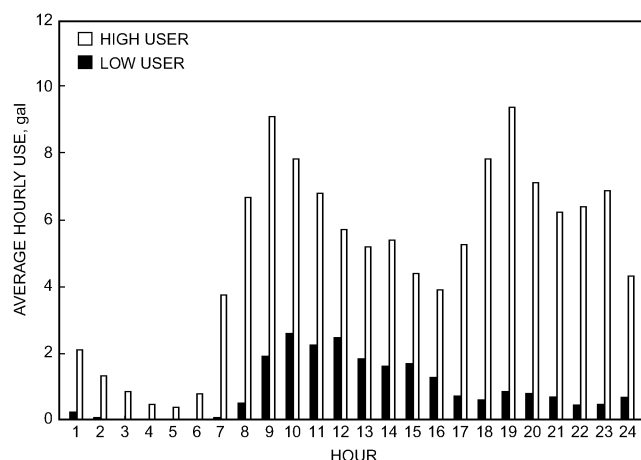


Fig. 14 Residential Average Hourly Hot-Water Use Patterns for Low and High Users

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.

Additional Data.

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 250 to 500 gal per day (EPRI 1994).

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 300 to 1000 gal per day (EPRI 1994).

Apartments. Table 7 shows cumulative hot-water use over time for apartment buildings, 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 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 15. 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 lowest 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

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

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

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	3.8 gal/student	22.0 gal/student	13.1 gal/student
Women's dormitories	5.0 gal/student	26.5 gal/student	12.3 gal/student
Motels: Number of units ^a			
20 or less	6.0 gal/unit	35.0 gal/unit	20.0 gal/unit
60	5.0 gal/unit	25.0 gal/unit	14.0 gal/unit
100 or more	4.0 gal/unit	15.0 gal/unit	10.0 gal/unit
Nursing homes	4.5 gal/bed	30.0 gal/bed	18.4 gal/bed
Office buildings	0.4 gal/person	2.0 gal/person	1.0 gal/person
Food service establishments			
Type A: Full-meal restaurants and cafeterias	1.5 gal/max meals/h	11.0 gal/max meals/day	2.4 gal/average meals/day ^b
Type B: Drive-ins, grills, luncheonettes, sandwich, and snack shops	0.7 gal/max meals/h	6.0 gal/max meals/day	0.7 gal/average meals/day ^b
Apartment houses: Number of apartments			
20 or less	12.0 gal/apartment	80.0 gal/apartment	42.0 gal/apartment
50	10.0 gal/apartment	73.0 gal/apartment	40.0 gal/apartment
75	8.5 gal/apartment	66.0 gal/apartment	38.0 gal/apartment
100	7.0 gal/apartment	60.0 gal/apartment	37.0 gal/apartment
200 or more	5.0 gal/apartment	50.0 gal/apartment	35.0 gal/apartment
Elementary schools	0.6 gal/student	1.5 gal/student	0.6 gal/student ^b
Junior and senior high schools	1.0 gal/student	3.6 gal/student	1.8 gal/student ^b

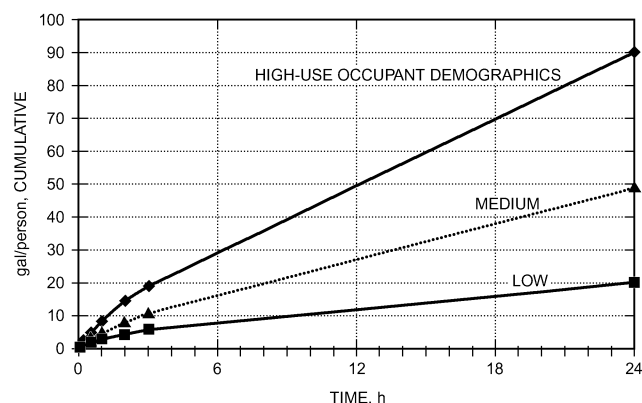
*Data predate modern low-flow fixtures and appliances.

^aInterpolate for intermediate values.^bPer day of operation.**Table 7 Hot-Water Demand and Use Guidelines for Apartment Buildings
(Gallons per Person at 120°F Delivered to Fixtures)**

Guideline	Peak Minutes						Maximum Daily	Average Daily
	5	15	30	60	120	180		
Low	0.4	1.0	1.7	2.8	4.5	6.1	20	14
Medium	0.7	1.7	2.9	4.8	8.0	11.0	49	30
High	1.2	3.0	5.1	8.5	14.5	19.0	90	54

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 15 generates a water-heating equipment sizing method for apartment buildings. The cumulative total hot-water consumption versus time (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. The key is that plots of cumulative total hot-water consumption versus time as shown in Figure 15 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 point in time. Up to any point in time, the minimum average heating rate needed to satisfy the load is one that can heat the average hot-water flow rate through that time from the local entering cold-water temperature to the water-heating system delivery temperature. (More accurately, the heating rate needed is determined by the local slope of the hot-water use versus time curve, not the average slope. This is because storage can supply the hot water supplied up to a selected time, and the heating rate only needs to provide the additional energy after storage is depleted. Eventually, however, storage needs to be reheated, which must also

**Fig. 15 Apartment Building Cumulative Hot-Water Use Versus Time (from Table 7)**

be considered. See the two methods illustrated in Example 1.) The storage volume needed for that heating rate is the total cumulative flow through that time (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 15 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.

Sizing Examples

Example 1. 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 120°F, design entering cold-water temperature of 40°F, and heating device thermal efficiency of 80%.

Simplified Method.

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.

At 5 min, the peak design cumulative volume is $(0.7 \text{ gal}) \times (198 \text{ people}) = 138.6 \text{ gal}$. The average flow rate over 5 min is $138.6 \text{ gal} / 5 \text{ min} = 27.72 \text{ gal/min}$. The required heating rate is thus, from Equation (1) and dividing by the input efficiency,

$$q = (27.72 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot ^\circ\text{F}) \times (120 - 40^\circ\text{F})/0.8 = 1,397,088 \text{ Btu/h}$$

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

$$V = 138.6 \text{ gal}/0.7 = 198 \text{ gal}$$

Note that, because the heating rate divided by storage capacity (7056 Btu/h·gal) exceeds 4000 Btu/h·gal, this system is considered an instantaneous water heater.

At 60 min, $(4.8 \text{ gal/person})(198 \text{ people}) = 950.4 \text{ gal}$. Average flow rate = $950.4 \text{ gal}/60 \text{ min} = 15.8 \text{ gal/min}$.

$$q = (15.8 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot ^\circ\text{F}) \times (120 - 40^\circ\text{F})/0.8 = 798,336 \text{ Btu/h}$$

$$V = 950.4 \text{ gal}/0.7 = 1358 \text{ gal}$$

Doing these calculations at other volumes and times yields the combinations of heating rate and storage volume that can serve the load (Table 8).

More Accurate Method.

The preceding simplified method calculates the needed heating rate by computing the average water flow rate from the beginning of all draws for the day. In reality, because some storage is present, 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. Consequently, the simplified heating rate computational method works, but results in some degree of heating rate oversizing.

Solution: Using the more accurate heating rate sizing method is similar to using the simplified method, except the local slope of the hot-water use curve versus time must be found at each time interval to determine the necessary heating rate.

At 5 min, the peak design cumulative volume (Table 8) is 139 gal. At 15 min, the peak design cumulative volume (Table 8) is 337 gal. The incremental flow rate (representing the local slope of the hot water use line) is hence $(337 \text{ gal} - 139 \text{ gal})/10 \text{ min} = 19.8 \text{ gal/min}$. The needed heating rate is thus more accurately computed as

$$Q = (19.8 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot ^\circ\text{F}) \times (120^\circ\text{F} - 40^\circ\text{F})/0.8 = 997,920 \text{ Btu/h}$$

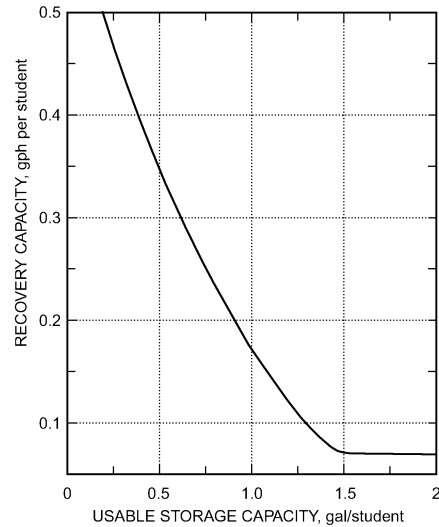
Note that heating rate divided by storage capacity (5040 Btu/h·gal) exceeds 4000 Btu/h·gal, so the more accurately sized system is still considered an instantaneous water heater.

From Table 8, the peak design cumulative volume at 120 min is 1584 gal, and is 2178 gal at 180 min. The incremental flow rate slope is thus $(2178 \text{ gal} - 1584 \text{ gal})/(180 \text{ min} - 120 \text{ min}) = 9.9 \text{ gal/min}$. The heating rate needed when using 1584 gal of storage is more accurately computed as

$$Q = (9.9 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot ^\circ\text{F}) \times (120^\circ\text{F} - 40^\circ\text{F})/0.8 = 498,960 \text{ Btu/h}$$

From Table 8, the peak design cumulative volume at 180 min is 2178 gal, and at 1440 min is 9702 gal. Consequently, the incremental flow rate slope is $(9702 \text{ gal} - 2178 \text{ gal})/(1440 \text{ min} - 180 \text{ min}) = 5.97 \text{ gal/min}$. The heating rate needed when using 2178 gal of storage is thus more accurately computed as

$$Q = (5.97 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot ^\circ\text{F}) \times (120^\circ\text{F} - 40^\circ\text{F})/0.8 = 300,888 \text{ Btu/h}$$

**Fig. 22 Elementary Schools**

It is important to recognize, however, when using this more accurate 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 more accurate combinations of heating rate and storage volume that can serve the load, as shown in Table.

There are several techniques to size water-heating systems using the more limited draw profile information in older data. Figures 16 to 23 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 16 to 23 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.

Ratings of gas-fired water-heating equipment are based on sea-level operation and apply up to 2000 ft. For operation above 2000 ft, and in the absence of specific recommendations from the local authority, equipment ratings should be reduced by 4% for each 1000 ft 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

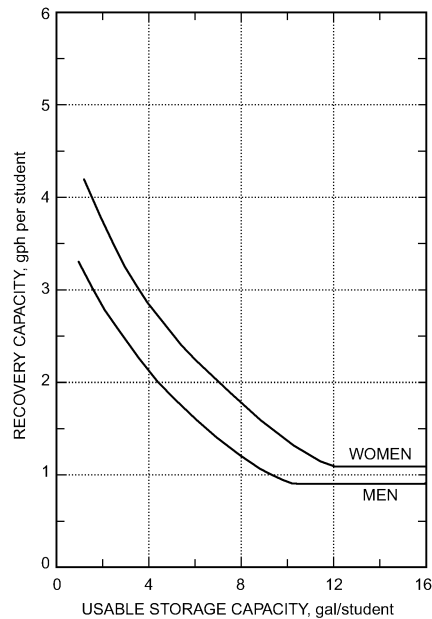
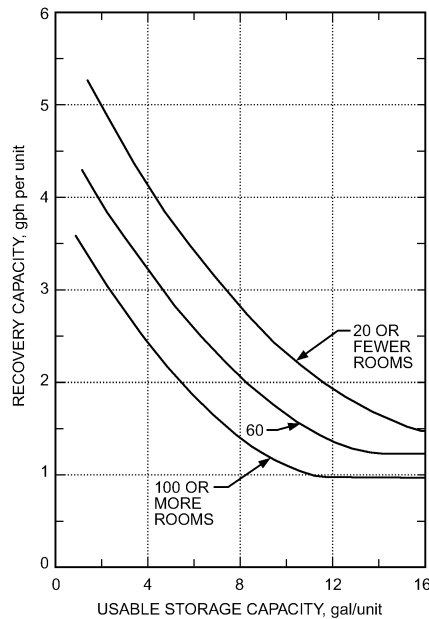
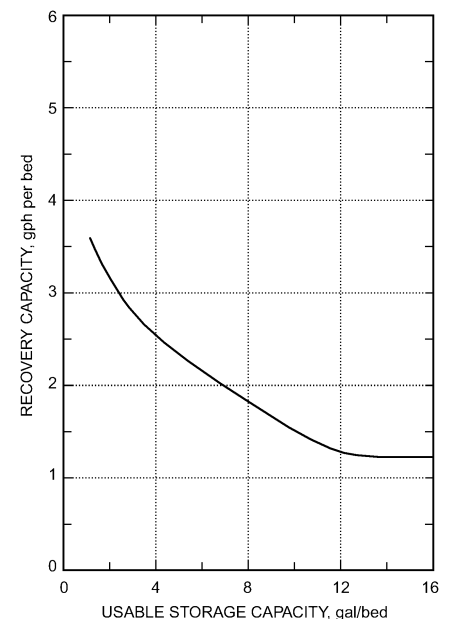
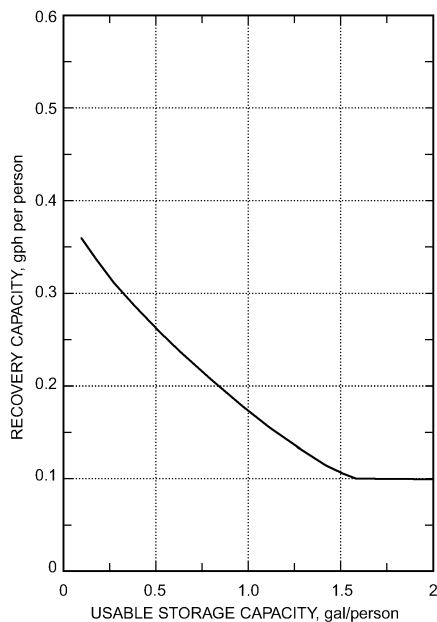
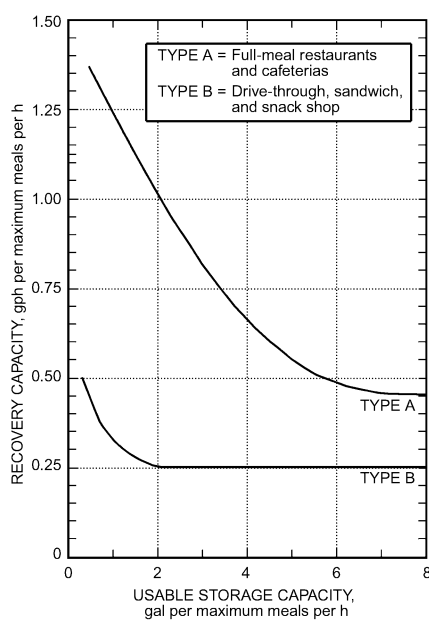
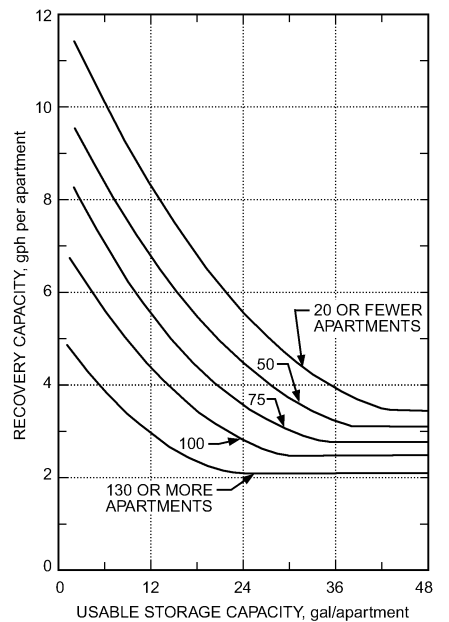
**Table 8 Example 1, Simplified Method:
Heating Rate and Storage Volume Options**

Time, min	Gallons per Person	Total Gallons for 198 People	Average Gallons per Minute	Heating Rate, Btu/h	Storage Volume, gal
5	0.7	139	28	1,397,088	198
15	1.7	337	22	1,130,976	481
30	2.9	574	19	964,656	820
60	4.8	950	16	798,336	1358
120	8	1584	13	665,280	2263
180	11	2178	12	609,840	3111
1440	49	9702	7	339,570	13,860

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.

Example 2. Determine the required water heater size for a 300-student women's dormitory for the following criteria:

- Storage with minimum recovery rate
- Storage with recovery rate of 2.5 gph per student
- With the additional requirement for a cafeteria to serve a maximum of 300 meals per hour for minimum recovery rate, combined with

**Fig. 16 Dormitories****Fig. 17 Motels****Fig. 18 Nursing Homes****Fig. 19 Office Buildings****Fig. 20 Food Service****Fig. 21 Apartments**

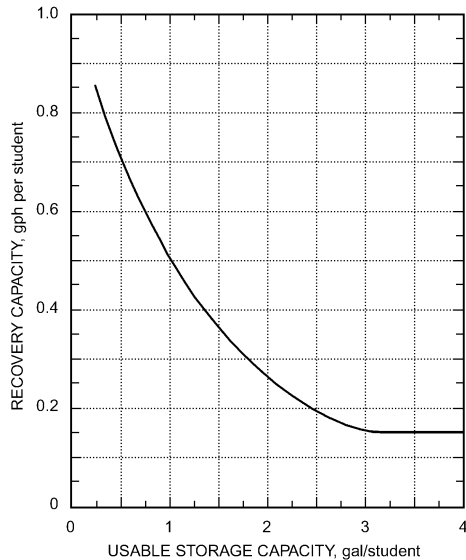


Fig. 23 High Schools

item *a*; and for a recovery rate of 1.0 gph per maximum meals per hour, combined with item *b*

Solution:

a. The minimum recovery rate from Figure 16 for women's dormitories is 1.1 gph per student, or 330 gph total. At this rate, storage required is 12 gal per student or 3600 gal total. On a 70% net usable basis, the necessary tank size is $3600/0.7 = 5150$ gal.

b. The same curve shows 5 gal storage per student at 2.5 gph recovery, or $300 \times 5 = 1500$ gal storage with recovery of $300 \times 2.5 = 750$ gph. The tank size is $1500/0.7 = 2150$ gal.

c. Requirements for a cafeteria can be determined from Figure 20 and added to those for the dormitory. For the case of minimum recovery rate, the cafeteria (Type A) requires $300 \times 0.45 = 135$ gph recovery rate and $300 \times 7/0.7 = 3000$ gal of additional storage. The entire building then requires $330 + 135 = 465$ gph recovery and $5150 + 3000 = 8150$ gal of storage.

With 1 gph recovery at the maximum hourly meal output, the recovery required is 300 gph, with $300 \times 2.0/0.7 = 860$ gal of additional storage. Combining this with item *b*, the entire building requires $750 + 300 = 1050$ gph recovery and $2150 + 860 = 3010$ gal of storage.

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

Example 3. Determine the water-heater size and monthly hot-water consumption for an office building to be occupied by 300 people under the following conditions:

- Storage with minimum recovery rate
- Storage with 1.0 gal per person storage
- 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
- Monthly hot-water consumption

Solution:

a. With minimum recovery rate of 0.1 gph per person from Figure 19, 30 gph recovery is required; storage is 1.6 gal per person, or $300 \times 1.6 = 480$ gal. If 70% of the hot water is usable, the tank size is $480/0.7 = 690$ gal.

b. The curve also shows 1.0 gal storage per person at 0.175 gph per person recovery, or $300 \times 0.175 = 52.5$ gph. The tank size is $300/0.7 = 430$ gal.

c. Hot-water requirements for a luncheonette (Type B) are in Figure 20. With a minimum recovery capacity of 0.25 gph per maximum meals per hour, 100 meals per hour requires 25 gph recovery, and the storage is 2.0 gal per maximum meals per hour, or $100 \times 2.0/0.7 =$

290 gal storage. The combined requirements with item *a* are then 55 gph recovery and 980 gal storage.

Combined with item *b*, the requirement is 77.5 gph recovery and 720 gal storage.

d. Average day values are found in Table 6. The office building consumes an average of 1.0 gal per person per day $\times$ 30 days per month $\times$ 300 people = 9000 gal per month and the luncheonette will consume 0.7 gal per meal $\times$ 200 meals per day $\times$ 22 days per month = 3100 gal per month, for a total of 12,100 gal per month.

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

Example 4. Determine the water heater size for a 200-unit apartment house under the following conditions:

- Storage with minimum recovery rate
- Storage with 4 gph per apartment recovery rate
- Storage for each of two 100-unit wings
 - Minimum recovery rate
 - Recovery rate of 4 gph per apartment

Solution:

a. The minimum recovery rate, from Figure 21, for apartment buildings with 200 apartments is 2.1 gph per apartment, or a total of 420 gph. The storage required is 24 gal per apartment, or 4800 gal. If 70% of this hot water is usable, the necessary tank size is $4800/0.7 = 6900$ gal.

b. The same curve shows 5 gal storage per apartment at a recovery rate of 4 gph per apartment, or $200 \times 4 = 800$ gph. The tank size is $200 \times 5/0.7 = 1400$ gal.

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

1. With minimum recovery rate of 2.5 gph per apartment (see Figure 21), a 250 gph recovery is required, and the necessary storage is 28 gal per apartment, or $100 \times 28 = 2800$ gal. The required tank size is $2800/0.7 = 4000$ gal for each wing.

2. The curve shows that, for a recovery rate of 4 gph per apartment, storage is 14 gal per apartment, or $100 \times 14 = 1400$ gal, with recovery of $100 \times 4 = 400$ gph. The necessary tank size is $1400/0.7 = 2000$ gal in

- Storage with minimum recovery rate
- each wing.

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

Example 5. Determine the water-heater size and monthly hot-water consumption for a 2000-student high school under the following conditions:

- Storage with minimum recovery rate
- Storage with 4000 gal maximum storage capacity
- Monthly hot-water consumption

Solution:

a. With the minimum recovery rate of 0.15 gph per student (from Figure 23) for high schools, 300 gph recovery is required. The storage required is 3.0 gal per student, or $2000 \times 3.0 = 6000$ gal. If 70% of the hot water is usable, the tank size is $6000/0.7 = 8600$ gal.

b. Net storage capacity is $0.7 \times 4000 = 2800$ gal, or 1.4 gal per student. From the curve, a recovery capacity of 0.37 gph per student or $2000 \times 0.37 = 740$ gph is required.

c. From Table 6, monthly hot-water consumption is 2000 students $\times$ 1.8 gal per student per day $\times$ 22 days = 79,000 gal.

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

Table 10 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. 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 10 are no longer valid. In all cases, total demand is never less than the demand for the largest single fixture. The heater or coil

Service Water Heating

50.19

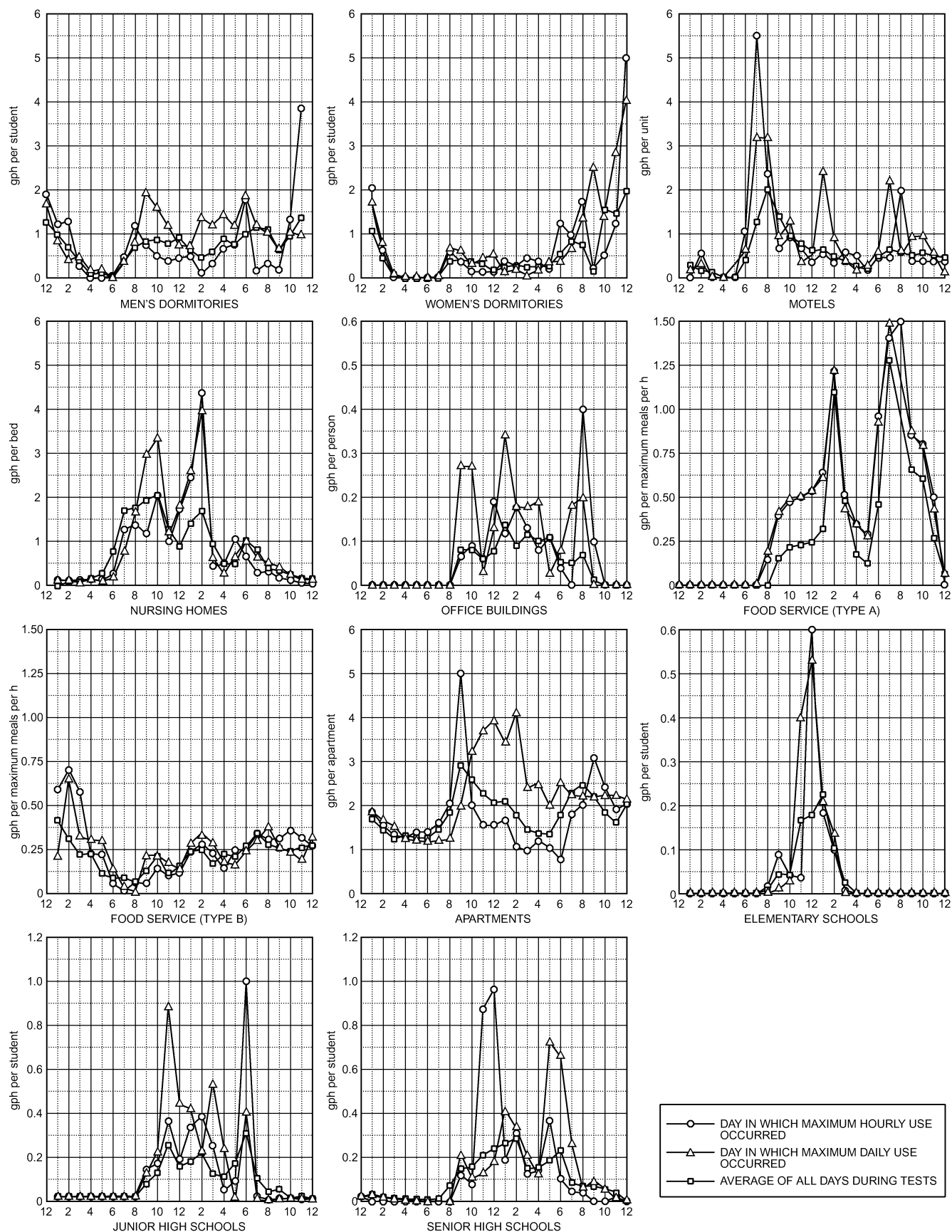


Fig. 24 Hourly Flow Profiles for Various Building Types

Table 9 Example 1, More Accurate Method: Heating Rate and Storage Volume Options

Time, min	Gallons per Person	Total Gallons for 198 People	Local Slope of Incremental Gallons per Minute	Heating Rate, Btu/h	Storage Volume, gal
5	0.7	139	19.8	997,920	198
15	1.7	337	15.8	796,320	481
30	2.9	574	12.5	630,000	820
60	4.8	950	10.6	534,240	1,358
120	8	1584	9.9	498,960	2,263
180	11	2178	5.97	339,570	3,111
1440	49	9702	7	339,570	13,860

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

Table 10 Hot-Water Demand per Fixture for Various Types of Buildings

(Gallons of water per hour per fixture, calculated at a final temperature of 140°F)

	Apartment House	Club	Gymnasium	Hospital	Hotel	Industrial Plant	Office Building	Private Residence	School	YMCA
1. Basin, private lavatory	2	2	2	2	2	2	2	2	2	2
2. Basin, public lavatory	4	6	8	6	8	12	6	—	15	8
3. Bathtub ^c	20	20	30	20	20	—	—	20	—	30
4. Dishwasher ^a	15	50-150	—	50-150	50-200	20-100	—	15	20-100	20-100
5. Foot basin	3	3	12	3	3	12	—	3	3	12
6. Kitchen sink	10	20	—	20	30	20	20	10	20	20
7. Laundry, stationary tub	20	28	—	28	28	—	—	20	—	28
8. Pantry sink	5	10	—	10	10	—	10	5	10	10
9. Shower	30	150	225	75	75	225	30	30	225	225
10. Service sink	20	20	—	20	30	20	20	15	20	20
11. Hydrotherapeutic shower				400						
12. Hubbard bath				600						
13. Leg bath				100						
14. Arm bath				35						
15. Sitz bath				30						
16. Continuous-flow bath				165						
17. Circular wash sink				20	20	30	20		30	
18. Semicircular wash sink				10	10	15	10		15	
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.

^aDishwasher requirements should be taken from this table or from manufacturers' data for model to be used, if known.

^bRatio 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.

^cWhirlpool baths require specific consideration based on capacity. They are not included in the bathtub category.

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

Solution:

60 lavatories	×	2 gph	=	120 gph
30 bathtubs	×	20 gph	=	600 gph
30 showers	×	30 gph	=	900 gph
60 kitchen sinks	×	10 gph	=	600 gph
15 laundry tubs	×	20 gph	=	300 gph
Possible maximum demand			=	2520 gph
Probable maximum demand	=	2520 × 0.30	=	756 gph
Heater or coil capacity			=	756 gph
Storage tank capacity	=	756 × 1.25	=	945 gal

Showers. In many housing installations such as motels, hotels, and dormitories, peak hot-water load is usually from shower use. Table 10 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 40 psi water pressure, available shower heads have nominal flow rates of blended hot and cold water from about 2.5 to 6 gpm. 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 1.5 to 4.0 gpm.

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	2.5 gpm
Medium shower head	4.5 gpm
Large shower head	6 gpm

Note that the maximum flow rate allowed by U.S. federal energy efficiency standards is 2.5 gpm, as of 1992. However, higher-flow-rate models are still sold.

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 11 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 5 gpm to a federally mandated maximum flow rate of 1.6 gpm, and, similarly, flow rate requirements for aerators on public hand sinks have dropped from 2.2 gpm to 0.5 gpm.

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

Table 11 Hot-Water Requirements for Various Commercial Kitchen Uses

Equipment ^a	Storage, gph	Tankless, gpm
Hand sink or lavatory	5	0.5
One-compartment food preparation or utility sink	5	2.0
Two-compartment food preparation or utility sink	10	2.0
Large three-compartment sanitation sink (24 × 24 × 14 in.)	105 ^b	2.0 ^c
Standard three-compartment sanitation sink (18 × 18 × 10 in.)	42 ^b	2.0 ^c
Bar three-compartment sanitation sink (10 × 14 × 10 in.)	18 ^b	2.0
Mop sink or can wash facility	15	2.0 ^c
Prerinse spray valve	45	Varies
Dishwasher	Varies ^d	Varies

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

^aRefer to manufacturer's specifications for other end-use fixtures that use hot water.

^bEquation to calculate storage heater hot-water demand requirements for sanitation sinks:

$$\text{gph} = \text{Sink size (in}^3\text{)} \times \text{Number of compartments} \times 7.5 \text{ gal/ft}^3 + 1728 \text{ in}^3/\text{ft}^3$$

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.

^cA flow rate of 5 gpm is recommended for compartment sink or hose bibb fill operations.

^dCertain 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.

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 11, 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, Btu/h

Q_h = flow rate, gph

c_p = specific heat of water = 1.00 Btu/lb · °F

ρ = density of water = 8.33 lb/gal

Δt = temperature rise, °F

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

Table 12 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 gpm	Hourly Demand for Heaters with Storage, ^b gph
Undercounter (low-temperature)	2.1 to 4.4	22 to 65
Undercounter (high-temperature)	3.2 to 6.6	19 to 51
Door type (low-temperature)	1.9 to 5.1	33 to 68
Door type (high-temperature)	2.7 to 7.1	28 to 92
Rack conveyor (low-temperature)	1.3 to 4.8	78 to 290
Rack conveyor (high-temperature)	0.7 to 4.8	44 to 290
Flight conveyor (high-temperature)	1.0 to 6.0	57 to 360

^aBased on flow rate during rinse operation period.^bBased on dishwasher operation at 100% of mechanical capacity.

delivery of 140°F water for rinse operation, but inlet temperature can range from a minimum of 120°F for a low-temperature dishwasher to 180°F 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 145 to 150°F) to deliver 140°F water to the dishwasher or booster heater.

In restaurants, bacteria are killed by rinsing washed dishes with 180 to 195°F water for several seconds. In addition, an ample supply of general-purpose hot water, usually at 140 to 150°F, is required for the wash cycle of dishwashers. Although a water temperature of 140°F is reasonable for dish washing in private dwellings, in public places, the NSF (e.g., *Standard 3*) or local health departments require 180 to 195°F water in the rinsing cycle. However, the NSF allows a lower temperature of 120 to 140°F 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 180°F water should be confined to the equipment requiring it and should be obtained by boosting the temperature. It is dangerous to distribute 180°F 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 12 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 pre-heat the cold water for the next rinse cycle.

Examples 7, 8, and 9 demonstrate the use of Equation (11) in conjunction with Tables 11 and 12.

Example 7. 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 1.15 gpm spray valve, and one high-temperature door-type dishwasher (1.0 gal/rack, 11 s rinse time, 57 racks/h) with a built-in 40°F 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, gpm	Recovery Rate Required, gph
One-comp. prep sink	2	5
Three-comp. sink	2	44
Hand sink (2)	1	10
Lavatory (2)	1	10
Mop sink	2	15
Prerinse sink	1.15	45
Dishwasher	5.45	57
Total requirements	14.6	186

The minimum flow rate for sizing the heating rate of a tankless water heater is 14.6 gpm. Likewise, the minimum flow rate for sizing the heating rate of a storage water heater is 186 gph.

Example 8. Determine the energy input requirements (heating rate) for both a tankless and a storage water heater for the commercial kitchen described in Example 7. 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 50°F and the water heater outlet temperature is 150°F. This is a little higher than the 140°F required by the dishwasher booster heater, to account for piping heat losses.

Solution: The temperature rise required is $150 - 50 = 100^\circ\text{F}$. For a tankless water heater, the required heating rate using Equation (11) is computed as

$$q_i = (14.6 \text{ gal/min})(60 \text{ min/h})(8.33 \text{ lb/gal})(1 \text{ Btu/lb}\cdot^\circ\text{F})(100^\circ\text{F}) = 729,708 \text{ Btu/h}$$

Thus, for the 70% gas tankless option, the required energy input rate is $729,708/0.70 = 1,042,440 \text{ Btu/h}$. It is common practice to install one or more 199,000 Btu/h units in parallel in commercial facilities to meet minimum flow rate requirements. Using this approach, six standard-efficiency tankless units, each rated at 199,000 Btu/h, are required to meet this load. For the 85% gas condensing tankless option, the required heating rate is $729,708/0.85 = 858,480 \text{ Btu/h}$, requiring five 199,000 Btu/h condensing tankless heaters. For the 99% electric tankless option, the required energy input rate is $729,708/0.99 = 737,079 \text{ Btu/h}$. Four 184,000 Btu/h or six 123,000 Btu/h 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 199,000 Btu/h standard-efficiency heater typically provides a maximum of 3.3 gpm of water at a 100°F temperature rise, whereas a condensing heater provides 3.8 gpm. To meet the flow requirements of 14.6 gpm for this facility, five standard-efficiency 199,000 Btu/h units installed in parallel for a combined input rate of 995,000 Btu/h are required to meet the load by providing a maximum combined flow rate of 16.5 gpm. To meet the flow requirements with condensing high-efficiency tankless heaters, four 199,000 Btu/h units for a combined input rate of 796,000 Btu/h are required, for a maximum combined flow rate of 15.2 gpm. 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 14.6 gpm 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

$$q_i = (186 \text{ gal/h})(8.33 \text{ lb/gal})(1 \text{ Btu/lb}\cdot^\circ\text{F})(100^\circ\text{F}) = 154,938 \text{ Btu/h}$$

Thus, for the 70% gas storage water heater, the required heating rate is $154,938/0.70 = 221,340 \text{ Btu/h}$. For the 85% gas condensing storage water heater, the required heating rate is $154,938/0.85 =$

182,280 Btu/h. For the 90% electric resistance storage water heater, the required heating rate is $154,938/0.90 = 172,153$ Btu/h.

Note that this information is 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 250,000 Btu/h gas storage heater (or two 120,000 Btu/h 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 199,000 Btu/h 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 184,000 Btu/h or two 92,000 Btu/h electric resistance storage heaters could be selected from manufacturers' specification sheets to meet the hot-water demand.

Example 9. For the commercial kitchen described in Example 7, 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 20°F from 150°F. 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 7 drops from 186 gph to 129 gph 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

$$q_i = (129 \text{ gal/h})(8.33 \text{ lb/gal})(1 \text{ Btu/lb} \cdot ^\circ\text{F})(80^\circ\text{F}) = 85,966 \text{ Btu/h}$$

For the 90% gas condensing storage water heater, the required heating rate is $85,966/0.90 = 95,517$ Btu/h. One 100,000 Btu/h 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 110°F. They rely on larger secondary heating systems commonly referred to as booster heaters to heat the water to the 180°F sanitizing rinse temperature on a high-temperature machine. This requires the addition of a 70°F rise booster heater instead of a conventional 40°F booster heater that would be used in conjunction with entering 140°F 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 180°F 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 120°F. Some manufacturers recommend a temperature of 160°F; however, the average appears to be 140°F. 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

$$F = NPV_f/T \quad (12)$$

where

F = peak draw, gpm

N = number of washers installed

P = number of washers drawing hot water divided by N

V_f = quantity of hot water supplied to machine during hot-wash fill, gal

T = wash fill period, min

Recovery rate can be calculated from

$$R = 60NPV_f/(\theta + 10) \quad (13)$$

where

R = total hot water (machines adjusted to hottest water setting), gph

θ = actual machine cycle time, min

Note: $(\theta + 10)$ 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 weight of the material processed. Average hot-water requirements at 180°F are

Institutional	2 gal/lb·h
Commercial	2 gal/lb·h
Linen supply	2.5 gal/lb·h
Industrial	2.5 gal/lb·h
Diaper	2.5 gal/lb·h

Total weight of the material times these values give the average hourly hot-water requirements. The designer must consider peak requirements; for example, a 600 lb machine may have a 20 gpm average requirement, but the peak requirement could be 350 gpm.

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, reclaimers, 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 6 in. above the heating element to a point 12 in. 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 135°F wastewater is discharged to the sewer. Fresh water can be conservatively preheated to within 15°F of the wastewater temperature for the next operation in the wash cycle. Regions with an annual average temperature of 55°F can increase to 120°F the initial temperature of fresh water going into the hot-water heater. For each 1000 gph or 8330 lb per hour of water preheated 65°F (55 to 120°F), heat reclamation and associated energy savings is 540,000 Btu/h.

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 10 to 20°F above the existing makeup temperature.

Swimming Pools/Health Clubs. The desirable temperature for swimming pools is 80°F. 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 80°F 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 100,000 Btu/h. 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

$$\text{Area} = 3.14AB$$

A = Short radius

B = Long radius

$$\text{Volume} = 7.5 \text{ gal/ft}^3 \times \text{Area} \times \text{Average Depth}$$

Kidney Shaped

$$\text{Area} = 0.45L(A+B) \text{ (approximately)}$$

L = Length

A = Width at one end

B = Width at other end

$$\text{Volume} = 7.5 \text{ gal/ft}^3 \times \text{Area} \times \text{Average Depth}$$

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

$$\text{Area} = 3.14R^2 + LW$$

L = Length of straight sides

W = Width or $2R$

R = Radius of ends

$$\text{Volume} = 7.5 \text{ gal/ft}^3 \times \text{Area} \times \text{Average Depth}$$

Rectangular

$$\text{Area} = LW$$

L = Length

W = Width

$$\text{Volume} = 7.5 \text{ gal/ft}^3 \times \text{Area} \times \text{Average Depth}$$

The following is an effective method for heating outdoor pools. Additional equations can be found in [Chapter 5](#).

1. Obtain pool water capacity, in gallons.
2. Determine the desired heat pickup time in hours.
3. Determine the desired pool temperature. If not known, use 80°F.
4. Determine the average temperature of the coldest month of use.

The required heater output q_1 can now be determined by the following equations:

$$q_1 = \rho c_p V(t_f - t_i)/\theta \quad (14)$$

where

q_1 = pool heat-up rate, Btu/h

ρ = density of water = 8.33 lb/gal

c_p = specific heat of water = 1.00 Btu/lb·°F

V = pool volume, gal

t_f = desired temperature (usually 80°F)

t_i = initial temperature of pool, °F

θ = pool heat-up time, h

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

where

q_2 = heat loss from pool surface, Btu/h

U = surface heat transfer coefficient = 10.5 Btu/h·ft²·°F

A = pool surface area, ft²

t_p = pool temperature, °F

t_a = ambient temperature, °F

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

Notes: These heat loss equations assume a wind velocity of 3 to 5 mph. For pools sheltered by nearby fences, dense shrubbery, or buildings, an average wind velocity of less than 3.5 mph can be assumed. In this case, use 75% of the values calculated by Equation (15). For a velocity of 5 mph, multiply by 1.25; for 10 mph, 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 1 gal of hot water for each clerical and light-industrial employee per work shift and 2 gal 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 13. The shower load depends on the flow rate of the shower heads and their length of use. Table 13 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.

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 70°F by adding hot water to the cold aggregate. Usually, water at about 150°F is considered proper for cold weather. If the water temperature is too high, some of the concrete will flash set.

Generally, 30 gal of hot water per cubic yard 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

Table 13 Hot-Water Usage for Industrial Wash Fountains and Showers

Type	Multiple Wash Fountains	Showers	
	Gal of 140°F Water Required for 10 min Period ^a	Flow Rate, gpm	Gal of 140°F Water Required for 15 min Period ^b
36 in. Circular	40	3	29.0
Semicircular	22	4	39.0
54 in. Circular	66	5	48.7
Semicircular	40	6	58.0

^aBased on 110°F wash water and 40°F cold water at average flow rates.

^bBased on 105°F shower water and 40°F cold water.

Table 14 Water Heater Sizing for Ready-Mix Concrete Plant
(Input and Storage Tank Capacity to Supply 150°F Water at 40°F Inlet Temperature)

Truck Capacity, yd ³	Water Heater Storage Tank Volume, gal	Time Interval Between Trucks, min*					
		50	35	25	10	5	0
		Water Heater Capacity, 1000 Btu/h					
6	430	458	612	785	1375	1830	2760
7.5	490	527	700	900	1580	2100	3150
9	560	596	792	1020	1790	2380	3580
11	640	687	915	1175	2060	2740	4120

*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 120 gal 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.

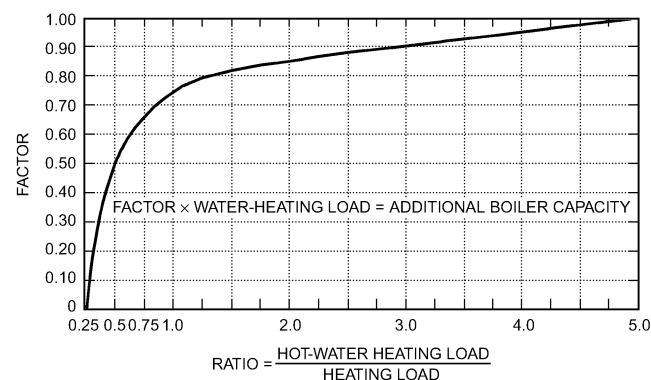


Fig. 25 Sizing Factor for Combination Heating and Water-Heating Boilers

exchangers must be used. Table 14 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 25 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 25 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

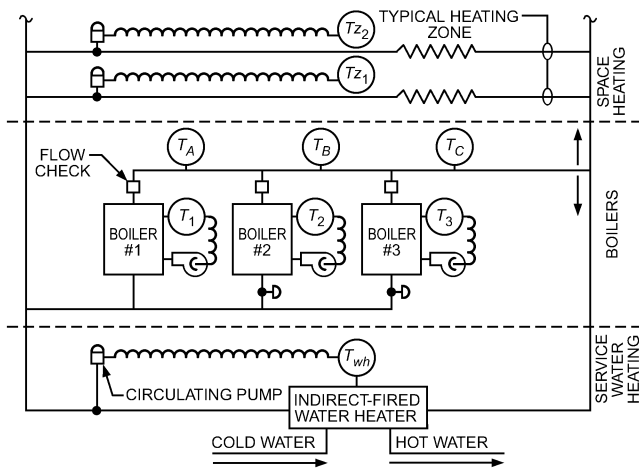


Fig. 26 Typical Modular Boiler for Combined Space and Water Heating

- 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.

The factor obtained from Figure 25 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 26 shows a typical modular boiler combination space- and water-heating arrangement.

Typical Control Sequence for Indirect Water Heaters

1. Any control zone or indirectly fired water heater thermostat (e.g., T_{z1} or T_{wh} in Figure 26) 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.

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. 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.

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.

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 15 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 105°F 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, 110°F is a more typical

Table 15 Needed Tankless Water Heater Output Heat Rates, Btu/h*

Flow Rate, gpm	Temperature Rise						
	10°F	25°F	50°F	55°F	75°F	77°F	100°F
0.1	504	1,260	2,520	2,772	3,780	3,881	5,040
0.5	2,520	6,300	12,600	13,860	18,900	19,404	25,200
1.0	5,040	12,600	25,200	27,720	37,800	38,808	50,400
1.5	7,560	18,900	37,800	41,580	56,700	58,212	75,600
2.0	10,080	25,200	50,400	55,440	75,600	77,6196	100,800
2.5	12,600	31,500	63,000	69,300	94,500	97,020	126,000
3.0	15,120	37,800	75,600	83,160	113,400	116,424	151,200
3.5	17,640	44,100	88,200	97,020	132,300	135,828	176,400
4.0	20,160	50,400	100,800	110,880	151,200	155,232	201,600
4.5	22,680	56,700	113,400	124,740	170,100	174,636	226,800
5.0	25,200	63,000	126,000	138,600	189,000	194,040	252,000
6.0	30,240	75,600	151,200	166,320	226,800	232,848	302,400
7.0	35,280	88,200	176,400	194,040	264,600	271,656	352,800
8.0	40,320	100,800	201,600	221,760	302,400	310,464	403,200
9.0	45,360	113,400	226,800	249,480	340,200	349,272	453,600
10.0	50,400	126,000	252,000	277,200	378,000	388,080	504,000

*Divide table values by input efficiency to determine required heat input rate. Values in Btu/h apply to fossil fuels, and those in kW apply to electric tankless heaters.

requirement. The needed temperature rise in a cold climate where the entering cold-water temperature may be 35°F would thus be 110°F – 35°F = 75°F; in a warm climate where the entering cold water temperature may be 85°F, the temperature rise would be 110°F – 85°F = 25°F. For comparison, the temperature rise specified in the U.S. federal water heater testing and rating procedure is 135°F – 58°F = 77°F. For reference, typical flow rate ranges are as follows:

- Hand-washing sinks: 0.2 to 1.0 gpm
- Showers: 0.8 to 2.5 gpm
- Bathtub fill rates: 1.0 to 6.0 gpm
- Dishwasher fill rates: 1.0 to 3.0 gpm
- Clothes-washing machine fill rates: 1.0 to 6.0 gpm
- Residential whole-house recurring peak rates: around 3.0 to 4.0 gpm
- Residential whole-house severe-peak flow rates: 6.0 to 8.0 gpm

As can be seen from Table 15, whole-house tankless water heaters need to be able to provide heating rates on the order of 75,000 to 150,000 Btu/h 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, because ASHRAE does not currently have a statistically valid amount of data on peak residential water/energy flow rates with which to make recommendations. 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.

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.

Fixture units (Table 16) are assigned to each fixture using hot water and totalled. Maximum hot-water demand is obtained from Figures 27 or 28 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.

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.

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

Table 16 Hot-Water Demand in Fixture Units (140°F 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.

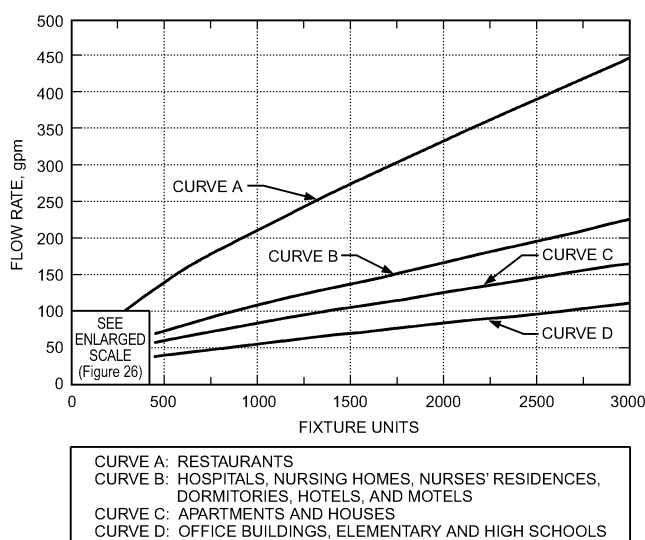


Fig. 27 Modified Hunter Curve for Calculating Hot-Water Flow Rate

(Data predate modern low-flow fixtures and appliances)

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 10 gpm, except for restaurants, for which it is 15 gpm. When system flow is not easily determined, the heater may be sized for full flow of the piping system at a maximum speed of 600 fpm. 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.

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 17 with Figure 27 or Figure 28. The result is usually higher than the demand determined from the actual fixture count. Actual heater size should be determined from Table 16. Hot-water consumption over time can be assumed to be

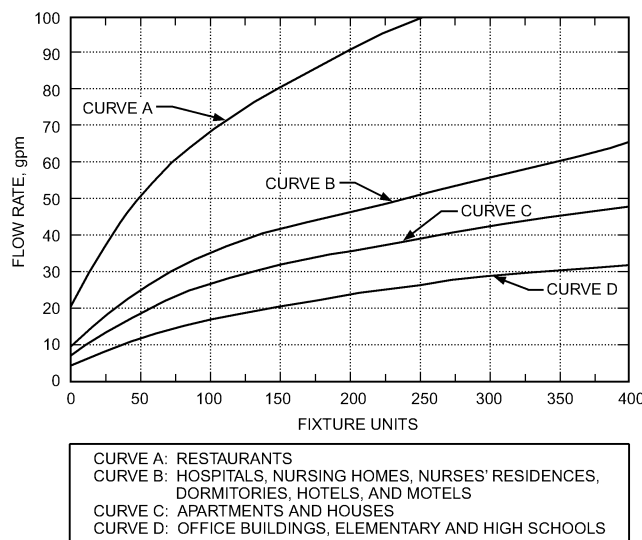


Fig. 28 Enlarged Section of Figure 27 (Modified Hunter Curve)

(Data predate modern low-flow appliances.)

Table 17 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).

the same as that in the section on Hot-Water Requirements and Storage Equipment Sizing.

Example 10. 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 8 gpm. Determine the hot-water flow rate for sizing a semi-instantaneous heater based on the following:

- Estimated number of fixture units
- Actual fixture count

Solution:

- Use Table 17 to find the estimated fixture count: 600 students $\times$ 0.3 fixture units per student = 180 fixture units. As showers are not included, Table 16 shows 1.5 fixture units per shower $\times$ 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 23 gpm.

b. To size the unit based on actual fixture count and Table 16, 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 28 shows 16 gpm, to which must be added the dishwasher requirement of 8 gpm. Thus, the total flow is 24 gpm.

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.

Sizing Refrigerant-Based Water Heaters

Refrigerant-based water heaters such as heat pump water heaters (HPWHs) and refrigeration heat reclaim systems cannot be sized like conventional systems to meet peak loads. The seasonal and instantaneous efficiency and output of these systems vary greatly with operating conditions. Computer software that performs detailed performance simulations taking these factors into account should be used for sizing and analysis. The capacities of these systems and any related supplemental water-heating equipment should be selected to achieve a high average daily run time (typically 12 to 24 h) and the lowest combination of operating and equipment cost. Heat pump water heater installations often benefit from having a greater ratio of storage tank capacity per unit of heating capacity than for conventional water-heating equipment. Because the heat input efficiency of heat pump water heaters is dramatically higher (200 to 300%) than conventional resistance and fossil-fuel-fired equipment, energy penalties from storage tank heat loss are substantially lower for heat pump water heater systems compared to conventional systems. Larger storage capacity allows use of smaller heat pumps, often reducing total system costs. For HPWHs, adequacy of the heat source and potential effect of air-source HPWH cooling output must be addressed.

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 11 to 14 include the following:

- Two fixtures 100 ft apart
- Six 5 min long draws per day of 1.0 gal/min, 105°F water at each fixture, spaced 3 min apart compared to 4 h apart
- Water heater output temperature of 120°F
- Tank-type fossil-fuel-fired water heater with input efficiency $\eta_i = 0.80$ and an energy factor of 0.59, yielding $UA_{tank} = 11.27 \text{ Btu/h} \cdot ^\circ\text{F}$, including energy input efficiency (note that tank heat loss rate is a function of energy factor rating, not tank size. However, for equal amounts of insulation, smaller tanks have higher energy factor rating)
- $T_{air} = 67.5^\circ\text{F}$ for both piping and tank
- $T_{cold} = 58^\circ\text{F}$ entering cold-water temperature
- Supply piping is 3/4 in. rigid copper with 1/2 in. thick foam insulation ($Mc_{p,w,p,i} = 0.2542 \text{ Btu/ft} \cdot ^\circ\text{F}$, (from Table 1) pipe volume = 0.02514 gal/ft)
- Return piping is 1/2 in. rigid copper with 1/2 in. 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 11. Assume a continuously running hot-water recirculation-loop system with an allowed loop temperature drop to the farthest fixture of 5°F, 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 115°F, using Equations (1) to (4) and (9).

$$\Delta T_{lm} = \frac{(120 - 67.5^\circ\text{F}) - (115 - 67.5^\circ\text{F})}{\ln[(120 - 67.5^\circ\text{F})/(115 - 67.5^\circ\text{F})]} = 49.96^\circ\text{F}$$

$$UA_{\text{flowing supply}} = 0.25 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F} \text{ (from Table 1)}$$

$$\begin{aligned} Q_{\text{piping supply}} &= (0.25 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})(100 \text{ ft})(49.96^\circ\text{F})/0.8 \\ &= (1561 \text{ Btu/h})(24 \text{ h/day}) \\ &= 37,470 \text{ Btu/day} \end{aligned}$$

$$\begin{aligned} m_{\text{circulating pump}} &= \frac{(1561 \text{ Btu/h})(0.8)}{(60 \text{ min/h})(8.25 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m\cdot^\circ\text{F})(5^\circ\text{F})} \\ &= 0.50 \text{ gal/min} \end{aligned}$$

$$UA_{\text{flowing return}} = 0.20 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F} \text{ (from Table 1)}$$

$$\begin{aligned} T_{\text{hot return out}} &= 67.5^\circ\text{F} + (115 - 67.5^\circ\text{F}) \\ &\quad \times e^{-\left\{ \frac{(0.20 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})(100 \text{ ft})}{(0.5 \text{ gal/min})(60 \text{ min/h})(8.25 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m\cdot^\circ\text{F})} \right\}} \\ &= 111.31^\circ\text{F} \end{aligned}$$

$$\begin{aligned} Q_{\text{piping return}} &= (0.50 \text{ gal/min})(60 \text{ min/h})(8.25 \text{ lb}_m/\text{gal}) \\ &\quad \times (1 \text{ Btu/lb}_m\cdot^\circ\text{F})(115 - 111.31^\circ\text{F})/0.8 \\ &= (1142 \text{ Btu/h})(24 \text{ h/day}) \\ &= 27,408 \text{ Btu/day} \end{aligned}$$

Next, determine the amount of hot water mixed with cold water to deliver the 105°F fixture delivery temperature, from Equation (24).

For the fixture at the water heater,

$$m_{\text{hot near}} = (1 \text{ gal/min})(105 - 58^\circ\text{F})/(120 - 58^\circ\text{F}) = 0.758 \text{ gal/min}$$

And for the far fixture,

$$m_{\text{hot far}} = (1 \text{ gal/min})(105 - 58^\circ\text{F})/(115 - 58^\circ\text{F}) = 0.825 \text{ gal/min}$$

Consequently,

$$\begin{aligned} Q_{\text{water near}} &= (0.758 \text{ gal/min})(8.33 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m\cdot^\circ\text{F}) \\ &\quad \times (120 - 58^\circ\text{F})(5 \text{ min/draw})(6 \text{ draws/day})/0.8 \\ &= 14,680 \text{ Btu/day} \end{aligned}$$

$$\begin{aligned} Q_{\text{water far}} &= (0.825 \text{ gal/min})(8.33 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m\cdot^\circ\text{F}) \\ &\quad \times (115 - 58^\circ\text{F})(5 \text{ min/draw})(6 \text{ draws/day})/0.8 \\ &= 14,689 \text{ Btu/day} \end{aligned}$$

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

$$\begin{aligned} Q_{\text{tank heat loss}} &= (11.27 \text{ Btu/h}\cdot^\circ\text{F})(120 - 67.5^\circ\text{F})(24 \text{ h/day}) \\ &= 14,200 \text{ Btu/day} \end{aligned}$$

Thus,

$$\begin{aligned} Q_{\text{total RL system}} &= 37,470 + 27,408 + 14,680 + 14,689 + 14,200 \\ &= 108,447 \text{ Btu/day} \end{aligned}$$

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

Example 12. 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 $T_{\text{hot out } 1} = 120^\circ\text{F}$. Then,

$$\begin{aligned} m_{\text{hot } 1} &= \frac{(1.0 \text{ gal/min})(105 - 58^\circ\text{F})}{(120 - 58^\circ\text{F})} \\ &= 0.758 \text{ gal/min [from Equation (17)]} \end{aligned}$$

$$T_{\text{hot out } 2} = 116.6^\circ\text{F [from Equation (2), where}$$

$$UA_{\text{flowing}} = 0.25 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}, L = 100 \text{ ft}]$$

$$m_{\text{hot } 2} = \frac{(1.0 \text{ gal/min})(105 - 58^\circ\text{F})}{(116.6 - 58^\circ\text{F})} = 0.80 \text{ gal/min}$$

$$T_{\text{hot out } 3} = 116.8^\circ\text{F}$$

$$m_{\text{hot } 3} = \frac{(1.0 \text{ gal/min})(105 - 58^\circ\text{F})}{(116.8 - 58^\circ\text{F})} = 0.7993 \text{ gal/min}$$

$$T_{\text{hot out } 4} = 116.79^\circ\text{F}$$

Thus,

$$\begin{aligned} Q_{\text{water far}} + Q_{\text{piping}} &= (0.7993 \text{ gal/min})(8.33 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m\cdot^\circ\text{F}) \\ &\quad \times (120 - 58^\circ\text{F})(5 \text{ min/draw})(6 \text{ draws/day})/0.8 \\ &= 15,480 \text{ Btu/day} \end{aligned}$$

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

$$Q_{\text{water near}} = \text{same as in Example 11} = 14,680 \text{ Btu/day}$$

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 $(120 + 116.79^\circ\text{F})/2 = 118.4^\circ\text{F}$.

Using $UA_{\text{zero flow}} = 0.15 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}$ from Table 1, and Equation (8),

$$\begin{aligned} T_{\text{pipe } 3 \text{ min}} &= 67.5^\circ\text{F} + (118.4 - 67.5^\circ\text{F}) \\ &\quad \times e^{-\left\{ \frac{(0.15 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})(3 \text{ min})}{(60 \text{ min/h})(0.2542 \text{ Btu/ft}\cdot^\circ\text{F})} \right\}} \\ &= 116.92^\circ\text{F} \end{aligned}$$

and

$$T_{\text{pipe } 4 \text{ h}} = 72.3^\circ\text{F}$$

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 losses.

From Equation (5),

$$\begin{aligned} Q_{\text{cd } 3 \text{ min}} &= (0.2542 \text{ Btu/ft}\cdot^\circ\text{F})(100 \text{ ft})(118.4 - 116.92^\circ\text{F}) \\ &\quad \times 5 \text{ cd/day}/0.8 + 1 \text{ cd (lumped into } Q_{\text{dump}}) \\ &= 235 \text{ Btu/day} \end{aligned}$$

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, $(1.5)(0.02514 \text{ gal/ft})(100 \text{ ft}) = 3.77 \text{ gal}$ of water must be dumped to drain.

$$\begin{aligned} Q_{\text{dump } 3 \text{ min}} &= (1 \text{ dump/day})(3.77 \text{ gal/dump})(8.33 \text{ lb}_m/\text{gal}) \\ &\quad \times (1 \text{ Btu/lb}_m\cdot^\circ\text{F})(120 - 58^\circ\text{F})/0.8 \\ &= 2434 \text{ Btu/day} \end{aligned}$$

$$Q_{\text{dump } 4 \text{ h}} = (6 \text{ dumps/day})(2434 \text{ Btu/dump}) = 14,604 \text{ Btu/day}$$

Table 18 Results Comparisons for Examples 11 to 14

System Type	3 min Draw Spacing			4 h Draw Spacing		
	Energy Use, Btu/day	Energy Use Compared to One Tank, %	Water Waste, gal/day	Energy Use, Btu/day	Energy Use Compared to One Tank, %	Water Waste, gal/day
Recirculation loop	108,447	231	0	108,447	184	0
One-tank	47,033	100	3.8	58,968	100	22.6
Two-tank (large)	57,760	123	0	57,760	98	0
Two-tank (small)	54,207	115	0	54,207	92	0

and

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

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

$$Q_{\text{tank heat loss}} = 14,200 \text{ Btu/day, as in Example 11}$$

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.

$$\begin{aligned} Q_{\text{total non-RL, 3 min spacing}} &= 15,480 + 14,680 + 235 + 2434 + 14,200 \\ &= 47,033 \text{ Btu/day} \end{aligned}$$

$$\begin{aligned} Q_{\text{total non-RL, 4 h spacing}} &= 15,480 + 14,680 + 0 + 14,604 + 14,200 \\ &= 58,968 \text{ Btu/day} \end{aligned}$$

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

$$t_{\text{wait}} = (3.77 \text{ gal}) / (1 \text{ gal/min}) = 3.77 \text{ min}$$

Example 13. 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.

$$Q_{\text{water}} = (2)(14,680 \text{ Btu/day}) = 29,360 \text{ Btu/day}$$

$$Q_{\text{tank heat loss}} = (2)(14,200 \text{ Btu/day}) = 28,400 \text{ Btu/day}$$

$$Q_{\text{total 2-tank}} = 29,360 + 28,400 = 57,760 \text{ Btu/day}$$

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

Example 14. 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 $\eta_i = 0.80$ and an energy factor of 0.61, yielding $UA_{\text{tank}} = 9.86 \text{ Btu/h}\cdot^\circ\text{F}$, including energy input efficiency,

$$Q_{\text{water}} = (2)(14,680 \text{ Btu/day}) = 29,360 \text{ Btu/day}$$

$$\begin{aligned} Q_{\text{tank heat loss}} &= (2)(9.86 \text{ Btu/h}\cdot^\circ\text{F})(120 - 67.5^\circ\text{F})(24 \text{ h/day}) \\ &= 24,847 \text{ Btu/day} \end{aligned}$$

$$Q_{\text{total 2-tank}} = 29,360 + 24,847 = 54,207 \text{ Btu/day}$$

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

Table 18 compares water and energy use of Examples 11 to 14, 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-water-heater 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 high *Legionella* concentrations, 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. For more specific water system design guidance, refer to ASHRAE *Standard* 188P (approval anticipated in 2015) and ASHRAE *Guideline* 12-2000.

Scalding

Scalding is an important concern in design and operation of potable hot-water systems. Figure 29 (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

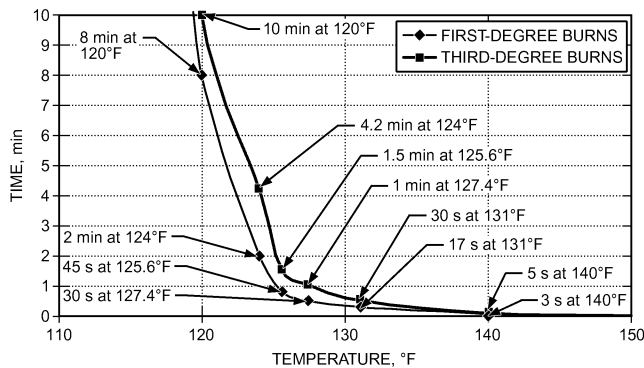


Fig. 29 Time for Adult Skin Burns in Hot Water

(e.g., 140°F and above), burns can occur almost instantaneously (3 s or less exposure). Even at lower temperatures such as 124°F, 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.

Temperature Requirement

Typical temperature requirements for some services are shown in Table 19. A 140°F 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 210°F 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 Btu/h) should equal or exceed the maximum out-put 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 210°F. These valves are typically applied to water heaters and hot-water storage tanks. The heat input temperature/steam rating (in Btu/h) 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

Table 19 Representative Hot-Water Temperatures

Use	Temperature, °F
Lavatory	
Hand washing	105
Shaving	115
Showers and tubs	110
Therapeutic baths	95
Commercial or institutional laundry, based on fabric	up to 180
Residential dish washing and laundry	140
Surgical scrubbing	110
Commercial spray-type dish washing ^a	
Single- or multiple-tank hood or rack type	
Wash	150 minimum
Final rinse	180 to 195
Single-tank conveyor type	
Wash	160 minimum
Final rinse	180 to 195
Single-tank rack or door type	
Single-temperature wash and rinse	165 minimum
Chemical sanitizing types ^b	140
Multiple-tank conveyor type	
Wash	150 minimum
Pumped rinse	160 minimum
Final rinse	180 to 195
Chemical sanitizing glass washer	
Wash	140
Rinse	75 minimum

^aAs required by NSF.

^bSee manufacturer for actual temperature required.

element located in the top 6 in. 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 120°F. 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.

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).

Scale formation is also affected by system requirements and equipment. As shown in Figure 30, 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 8 gr/gal, water softening or other water treatment is often recommended.

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,

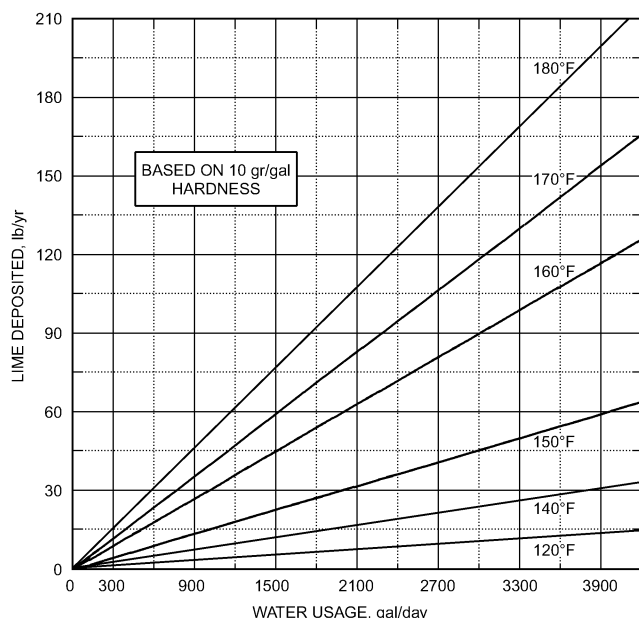


Fig. 30 Lime Deposited Versus Temperature and Water Use
(Based on data from Purdue University *Bulletin No. 74*)

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.

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.

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 and poor water system performance.

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 inline 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

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

where

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

However, Equation (11) 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 44,000 Btu/h and an input efficiency of 80% can raise the temperature of water being drawn through a storage tank at a rate of 3 gpm by approximately 23°F. If the entering cold-water temperature is 60°F, the water will be heated to only 83°F, 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

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

where

- V_a = usable water available from unfired tank, gal
- S_a = capacity of unfired tank, gal

Note: Assumes tank water at required temperature.

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

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

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

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 800 ft³ or ducted air is recommended. See manufacturer's literature for more information.

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