

Plumbing Notes

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1 248 CMR 10 – Sections

248 CMR 10.00 is the Uniform State Plumbing Code. It contains 22 sections. The sections are as follows:

1. **Scope and Jurisdiction.** What work and systems fall under the plumbing code. Covers plumbing installation, alteration, removal, replacement, repair, and construction. Sets the jurisdictional boundary at the potable-water connection to refrigeration, heating, cooling, ventilation, and fire sprinkler systems.
2. **Basic Principles.** The 27 basic principles behind the code: potable water, adequate pressure and volume, hot water, conservation, required fixtures, traps, venting, testing, sanitation, safety, and maintenance.
3. **Definitions.** Glossary for CMR 10. Defines fixtures, piping, systems, measurements, and other terms used throughout the code, with diagrams for selected definitions.
4. **Testing and Safety.** Surveying existing plumbing before work begins. Rough and finish testing and inspections, correction of defects, repairs and alterations, and disconnection when plumbing is removed.
5. **General Regulations.** Drainage pitch, changes of direction, allowed and prohibited fittings, trenching, bedding, and backfilling. Also covers structural safety, protection of piping, sewer connections, workmanship, manufacturer instructions, and temporary or emergency uses.
6. **Materials.** Allowed pipe, tubing, fittings, and other plumbing materials, including the standards and restrictions on their use. Separate tables for drainage and vent piping and for water distribution piping. Includes product acceptance and limits on plastic piping.
7. **Joints and Connections.** Joining methods for each piping material. Covers soldered, brazed, mechanical, threaded, solvent-cemented, and other joints; transitions between materials; unions; fixture connections; and waterproofing at penetrations.
8. **Traps and Cleanouts.** Required and prohibited traps, trap sizes, seals, setting, and protection. Cleanout locations, spacing, sizes, clearances, accessibility, and permitted equivalents. Includes cleanouts at stack bases and building drains.
9. **Interceptors, Separators, and Holding Tanks.** Where oil, gasoline, grease, sand, and other harmful wastes must be separated or contained. Covers installation, venting, flow controls, capacity, sizing, and maintenance. Includes grease-interceptor calculations and arrangements for sinks, dishwashers, and food waste disposers.
10. **Plumbing Fixtures.** Fixture materials, installation, and requirements for toilets, urinals, bathtubs, showers, drinking water stations, floor drains, dishwashers, laundry fixtures, and other equipment. Includes the minimum-facilities table by building occupancy.
11. **Hangers and Supports.** Support materials, attachment to the building, and allowance for expansion, contraction, and settlement. Maximum horizontal and vertical support intervals by pipe material and size, plus support at the base of stacks.
12. **Indirect Waste Piping.** Which equipment must discharge indirectly and which fixtures must connect directly. Air gaps and air breaks, receptors and sumps, clear water wastes, safe waste pans, pipe sizing, traps, venting, and systems serving multiple occupancies.
13. **Piping and Treatment of Special Wastes.** Treatment and neutralization before special wastes enter the drainage system. Requires design by a Massachusetts professional engineer. Covers materials, pipe labeling, independent venting, pH monitoring and alarms, limestone chip tanks, and industrial wastewater systems.
14. **Water Supply and the Water Distribution System.** Water pipe sizing using fixture factor values, occupancy demand factors, and pipe capacity tables. Also covers pressure, water hammer, installation, disinfection, hot water, water heaters and storage tanks, and protection against cross-connections and backflow.
15. **Sanitary Drainage System.** Drainage fixture-unit values and sizing of horizontal drains, branches, and stacks. Covers stack offsets, underground piping, kitchen sink drainage, future fixtures, sumps and ejectors, and protection of fixtures subject to backflow.
16. **Vents and Venting.** Permitted and prohibited venting arrangements. Covers vent stacks and stack vents, roof terminals, wet venting, stack venting, common vents, battery systems, bow vents, and fixture vents. Includes trap-to-vent distances, vent size and length tables, future vents, and ejector-sump venting.
17. **Storm Drains.** Sizing roof drains, horizontal storm drains, and vertical conductors using roof area and

rainfall. Covers sub-drains, sub-soil drains, backwater protection, and connections to combined systems. Explains where traps are required and where storm-only drainage does not require them.

18. **Hospital Fixtures.** Special definitions and requirements for clinic sinks, bedpan washers, sterilizers, and related equipment. Covers water supply protection, indirect wastes, special venting, vacuum systems, and sterilizer vent sizing.
19. **Manufactured/Mobile Homes, Modular Homes, Construction and Temporary Use Trailers.** Definitions and inspection requirements for these structures. Covers service connections, additions and renovations, inspection access in certified modular homes, and the material exemption for temporary-use trailers with toilet facilities.
20. **Swimming Pools.** Public, semi-public, residential, special purpose, and wading pool definitions. Covers permits and plan approval, cross-connection control, indirect waste connections, and authorization for discharge to storm or sanitary systems.
21. **Vacuum Powered Sanitary Drainage Systems.** Fixtures, piping, vacuum equipment, tanks, and connections to conventional drainage. Allows design by a Massachusetts professional engineer and requires installation according to the equipment manufacturer's instructions.
22. **Boiler Discharge to the Building Drainage System.** Water entering the drainage system must not exceed 150°F; boiler discharge pressure must not exceed 5 psi. Steam must first pass through a proper drain water tempering system or device. Also covers blow-off tanks, cooling devices, and backflow protection of the potable-water connection.

2 248 CMR 10.02 – Basic Principles

248 CMR 10.02 contains 27 basic principles for the design, installation, and maintenance of plumbing systems. The principles are as follows:

1. **Potable.** All occupied premises must have potable water. The supply must be protected from unsafe sources, backflow, backpressure, and back-siphonage.
2. **Adequate.** Fixtures, devices, and appurtenances must receive enough water, at adequate pressure, to function properly under normal use.
3. **Hot.** Hot water must be supplied in occupied premises to fixtures that use it for sanitary or hygienic purposes.
4. **Conservation.** Plumbing must meet the code's water conservation requirements and use the minimum amount of water needed to function properly.
5. **Overheating.** Water heating and storage equipment must be designed and installed to protect against explosion and overheating.
6. **Fixtures.** Each dwelling must have a toilet, lavatory, kitchen sink, and bathtub or shower. Washing machine connections must also be provided according to the dwelling and shared-laundry requirements. Other occupied buildings need sufficient sanitary facilities. Fixtures must be durable, smooth, nonabsorbent, corrosion resistant, and free of concealed fouling surfaces.
7. **Cleanouts.** Drainage systems must be designed, installed, and maintained to resist fouling, solids buildup, and stoppages. Adequate cleanouts must allow the system to be readily cleaned.
8. **Workmanship.** Piping and other components must use durable materials, be free of defective workmanship, and provide satisfactory service over their reasonably expected life.
9. **Traps.** Every fixture directly connected to drainage must have a liquid-seal trap. Drainage and vent piping must allow adequate air circulation. Trap seals must be protected from siphonage, leakage, aspiration, momentum, oscillation, backpressure, evaporation, and capillary action.
10. **Oil.** Oily and flammable liquid wastes require special precautions. Separators protect drainage systems from oil, grease, and flammable wastes at vehicle storage and repair facilities; see 248 CMR 10.09 for required locations and exceptions.
11. **Venting.** Vent terminals must extend to the outside air above the roof and be installed to prevent obstruction and the return of sewage gases into the building.
12. **Tested.** Plumbing systems must undergo the tests required by the code to reveal leaks and defects in materials and workmanship.
13. **Substances.** Keep substances out of sanitary drainage that cause stoppages, create explosive mixtures, damage piping or joints, or interfere with sewage disposal. Hazardous discharges must be collected for disposal or treated before entering the system.
14. **Indirect.** Indirect waste connections protect food, water, ice, sterile goods, and similar products from sewage contamination. Fixtures and equipment exposed to this backflow risk must connect indirectly to sanitary or storm drainage.
15. **Ventilation.** New or renovated rooms containing toilets, urinals, bathtubs, or showers must have proper lighting and mechanical exhaust to the outdoors. This principle does not apply to simply removing and replacing existing fixtures.
16. **Disposal.** All occupied premises must have a means of sewage disposal. Where a sewer is not within a reasonable distance, suitable disposal must comply with 248 CMR and 310 CMR 15.00 (Title 5).
17. **Flooding.** Drainage systems subject to sewage backflow from the public sewer must have protection against overflow into the building.
18. **Maintenance.** Plumbing systems must be kept safe and serviceable, both mechanically and from a health standpoint.
19. **Accessible.** Fixtures must have the clearances and access needed for use, cleaning, maintenance, and replacement.
20. **Integrity.** Plumbing work must preserve the structural integrity of the building. Related building requirements are covered by 780 CMR.
21. **Ground.** Discharges to ground or surface water must meet applicable local, state, and federal water quality discharge standards.
22. **Treatment.** Hazardous wastes must be carried in hazardous waste piping systems and collected for disposal or treated before entering sanitary drainage, as required by the code.

- 23. **Privacy.** In rooms with more than one toilet, or with both a toilet and a urinal, each toilet must be enclosed and each urinal must have side shielding.
- 24. **Drinking.** Drinking water stations must be in safe, clean areas free of hazards. They are prohibited in restrooms containing toilets or urinals.
- 25. **Temporary.** Transportable structures used for human shelter and kept on the same premises for no more than 30 days in a calendar year are exempt from the material provisions of 248 CMR 10.06. Construction trailers may remain for the duration of the project.
- 26. **Design.** Plumbing materials, products, methods, systems, design, and installation must comply with 248 CMR 3.00 through 10.00. Products used in plumbing or gas fitting systems must be accepted by the Board.
- 27. **Emergency.** Temporary use of a building with non-compliant plumbing because of an emergency or hardship requires approval by the Board and/or the Inspector acting under 248 CMR 10.05(19).

3 Water Column

Water Column

In plumbing theory, a *water column* is exactly what it sounds like—a vertical column filled with water, presumably weighted by the effect of gravity. For our purposes, we will consider straight columns with constant cross-sectional area in two essential cases: (i) circular cross section (Figure 1), (ii) rectangular cross section (Figure 2).

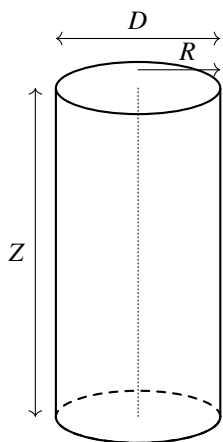


Figure 1. Cylindrical column.

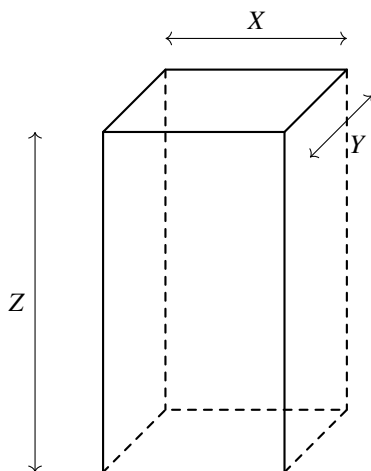


Figure 2. Rectangular column.

3.1 Cross Section

The *cross section* of a solid is a two-dimensional profile that would be exposed if the solid were sliced with a plane. We understand a cross section to be “sliced” perpendicular to the primary direction of length along the solid.

Circular Cross Section

When dealing with circles, it’s worth memorizing some digits of “pi”, written π , as:

$$\pi = 3.14159 \dots$$

The digits go on forever. Just remember $\pi \approx 3.14$ for short. The reason we have π at all is to relate the diameter D of a circle to its *circumference*, written C , which is the length around the circle:

$$C = \pi \times D$$

The *radius* of a circle, written R , is half the diameter of the circle:

$$R = \frac{D}{2}$$

In terms of the radius, the area of a circle, i.e. the area A of the circular cross section of a water column, is given by

$$A = \pi R^2.$$

Since plumbers usually deal with the diameter rather than the radius, we substitute $R = D/2$ to arrive at an equivalent area formula:

$$A = \pi \left(\frac{D}{2} \right)^2 = \pi \frac{D^2}{4}$$

Note that either formula for A respects the *units* expected for area. We know area is square-*something*, hence the presence of R^2 or D^2 on the right. If the radius or diameter is measured in inches, the area comes out in inches-squared.

Rectangular Cross Section

If instead we consider a water column that is more box-like, the cross section is a rectangle. For any rectangle, we may represent the sides as X and Y . (The height of the column is denoted Z .) In these variables, the *perimeter* of the column (a trip around the rectangle) is $X + Y + X + Y$. For perimeter calculations, use $C = 2X + 2Y$.

Using the same variables, the cross-sectional area is

$$A = X \times Y.$$

As expected, the units of A come out to the *square* of the units carried by X and Y . For clean calculations, these units should be matching (in $\times$ in or ft $\times$ ft). Be careful when mixing units. (You can avoid a lot of memorization by working in inches rather than feet.)

3.2 Column Capacity

The *volume* of a water column, synonymous with *capacity*, indicates how much water the column can hold. For these columns, the volume/capacity is determined by two factors: (i) the length (or height) of the column, and (ii) the

cross-sectional area of the column. The product of these equals the volume of water contained:

$$\text{Volume} = \text{Height} \times \text{Area}$$

We represent the volume as V , the height as Z , and the area as A . Thus the above is compactly written as

$$V = Z \times A.$$

Pay attention to the *units* carried by each factor in the above. Height Z is measured in inches or feet, however area A is measured in inches *squared* or feet *squared* (in^2 or ft^2). Multiplying height with area must always result in a volumetric unit such as inches cubed, feet cubed, or gallons (in^3 , ft^3 , gal). If someone tells you the volume of a container is 6 or 6 inches, they're *wrong*.

Volume Calculation

Going from our definition, the capacity or volume V of a water column with constant cross-sectional area is given by $V = Z \times A$, where Z is the height and A is the cross-sectional area. For circular pipes use $A = \pi R^2$ or $A = \pi D^2/4$. For rectangular pipes use $A = X \times Y$. Explicitly, this means:

$$\text{Circular: } V = Z \times (\pi D^2/4)$$

$$\text{Rectangular: } V = Z \times (X \times Y)$$

Supposing all calculations have been done in *inches*, then the result of the volume calculation will be in cubic inches. Use internal dimensions for capacity and external dimensions for outside surface area.

Conversion to Gallons

For any volume in cubic inches, the conversion to gallons can be done exactly without decimal approximation. Throughout these notes, gallons are US liquid gallons. We can take as a matter of definition that:

$$1 \text{ gallon} = 231 \text{ in}^3$$

That is, one gallon is 231 cubic inches.

In practice, the result of a volume calculation will look like

$$V = N \text{ in}^3,$$

where N is a unitless number because the in^3 factor is written explicitly. In order to convert to gallons, we must 'cancel out' cubic inches using the conversion factor above:

$$V = N \text{ in}^3 \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) = \frac{N}{231} \text{ gal}$$

This can be boiled down to "divide cubic inches by 231 and you've got gallons."

As a pure volume conversion, this analysis is not limited to water - it applies to any volume of space, whether occupied by a substance or empty.

Problem 1

One cubic inch is equal to how many gallons?

$$1 \text{ in}^3 = 1 \text{ in}^3 \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) = \frac{1}{231} \text{ gal} \\ \approx 0.0043290 \text{ gal}$$

Problem 2

One gallon is equal to how many cubic feet?

Answer:

$$1 \text{ gal} = 1 \text{ gal} \left(\frac{231 \text{ in}^3}{1 \text{ gal}} \right) \left(\frac{1 \text{ ft}}{12 \text{ in}} \right)^3 = \frac{231}{12^3} \text{ ft}^3 \\ \approx 0.13368 \text{ ft}^3$$

Problem 3

One cubic foot is equal to how many gallons?

Answer:

$$1 \text{ ft}^3 = 1 \text{ ft}^3 \left(\frac{12 \text{ in}}{1 \text{ ft}} \right)^3 \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) = \frac{12^3}{231} \text{ gal} \\ \approx 7.4805 \text{ gal}$$

Problem 4

If 3 inches of rain was trapped on a 62 ft long $\times$ 40 ft wide flat roof, how many gallons would that equal?

Answer:

$$V = 3 \text{ in} \times 62 \text{ ft} \left(\frac{12 \text{ in}}{1 \text{ ft}} \right) \times 40 \text{ ft} \left(\frac{12 \text{ in}}{1 \text{ ft}} \right) \\ = 3 \times 62 \times 40 \times 12^2 \text{ in}^3 \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) \approx 4637.9 \text{ gal}$$

Problem 5

A fifty-gallon drum (cylindrical) has an internal height of 3 feet. Calculate the diameter in inches.

Answer:

$$50 \text{ gal} \left(\frac{231 \text{ in}^3}{1 \text{ gal}} \right) = 3 \text{ ft} \left(\frac{12 \text{ in}}{1 \text{ ft}} \right) \times (\pi D^2/4) \\ D = \sqrt{\frac{50 \times 231 \times 4}{3 \times 12 \times \pi}} \text{ in} \approx 20.21 \text{ in}$$

Remark on Formula Quality

A plumbing license study guide *PHCC of MA* (Slide 25) poses the question: *What is the capacity in gallons of a 3-inch diameter pipe which is 27 inches long?* The solution is claimed to come from

$$\text{Capacity} = \text{Diameter}^2 \times \text{Length} \times 0.0034 .$$

While 0.0034 is calculator-ready, the suggested formula is incomplete unless its input and output units are specified. The formula obscures the geometry and unit conversions into decimal data, and offers no hint that capacity comes out in gallons and all lengths are in inches. With those units specified, the formula is a valid approximation. The student has to memorize chunks of setup information in order to deploy one fragile formula - and this must be done with nearly *every* formula.

It is *much* better for plumbers to attain a basic understanding of geometry and unit conversion so such formulas can be derived rather than memorized. There is no sane reason for memorizing hundreds of special cases, decimal numbers, or limiting circumstances. Let geometry rule each situation, not battalions of little rules.

For the example on hand, it just happens - and you're encouraged to prove this from what we said above - that the numerical factor comes from

$$\frac{\pi}{4 \times 231} \approx 0.003399992 .$$

Problem 6

Here the factors multiply numerical measurements in the stated units. The cylindrical gallon capacity formula

$$\text{Capacity} = \text{Diameter}^2 \times \text{Length} \times X$$

with $X \approx 0.0034$ only applies when the diameter and length are in inches. Derive similar factors Y, Z that apply for (i) diameter in inches and length in feet, (ii) diameter in feet and length in feet.

Answer:

$$Y = \frac{12\pi}{4 \times 231} \approx 0.04079990$$

$$Z = \frac{12^3\pi}{4 \times 231} \approx 5.875186$$

3.3 Column Surface Area

In the context of water columns, the surface area s (lowercase) of a column, not including the endcaps, is the product of the height and the cross-sectional perimeter. For a circle of diameter D , the perimeter is the same as the circumference, so $C = \pi D$. For a rectangle of sides X, Y , the perimeter is $C = 2X + 2Y$. For each case, we then have:

$$\text{Circular: } s = Z \times (\pi D)$$

$$\text{Rectangular: } s = Z \times 2 (X + Y)$$

Note that the *total* surface area S (uppercase) of a column must account for s and also the area of the two endcaps, A . Recall $A = \pi D^2/4$ for circles and $A = XY$ for rectangles:

$$\text{Total Surface Area} = s + 2A$$

Problem 7

How many square feet of insulation is required to wrap the outside of a (cylindrical) storage tank which is 18 inches in outside diameter and 5 feet long, including both flat endcaps? Ignore overlaps and insulation thickness.

Answer:

$$\begin{aligned} S &= Z \times (\pi D) + 2 \left(\pi D^2/4 \right) \\ &= 5 \text{ ft} \times (\pi \text{ } 18 \cancel{\text{ in}}) \left(\frac{1 \text{ ft}}{12 \cancel{\text{ in}}} \right) + 2 \left(\pi \frac{18^2}{4} \right) \cancel{\text{ in}}^2 \left(\frac{1 \text{ ft}}{12 \cancel{\text{ in}}} \right)^2 \\ &= \frac{5 \times \pi \times 18}{12} \text{ ft}^2 + \frac{2 \times \pi \times 18^2}{4 \times 12^2} \text{ ft}^2 \\ &\approx 27.096 \text{ ft}^2 \end{aligned}$$

Problem 8

A cube (box with $X = Y = Z$) is covered with three gallons of paint. The thickness of the paint is 0.005 inches. Assume all three gallons form a uniform coating on all six faces, without loss or shrinkage, and neglect the small corrections at edges and corners. Calculate the height of the box in feet.

Answer:

$$\begin{aligned} 3 \text{ gal} &\approx 0.005 \text{ in} \times 6Z^2 \\ 3 \cancel{\text{ gal}} \left(\frac{231 \text{ in}^2 \cancel{\text{ in}}}{1 \cancel{\text{ gal}}} \right) &\approx 0.005 \cancel{\text{ in}} \times 6Z^2 \end{aligned}$$

$$\begin{aligned} Z &\approx \sqrt{\frac{3 \times 231}{0.005 \times 6}} \cancel{\text{ in}} \left(\frac{1 \text{ ft}}{12 \cancel{\text{ in}}} \right) \\ &\approx 12.67 \text{ ft} \end{aligned}$$

3.4 Column Water Weight

The weight of water in a column is understood on a few assumptions. First, we assume approximately standard gravity. The conversion between kilograms and pounds of mass is fixed; gravity affects weight, not that conversion. Second, we assume the temperature of the water is in a range such that its mass density is close to 1000 kilograms per cubic meter. While conditions certainly vary, we will use the approximate weight per volume

$$\rho_{\text{water}} \approx 8.344 \frac{\text{lb}}{\text{gal}} .$$

Here ρ denotes weight density, also called specific weight, and lb means pounds-force in weight and pressure calculations. Don't worry about the greek character ρ ("rho"). Use d for "density" instead if you like. Either way, we gather that one gallon of water weighs about 8.344 pounds. We hold this approximate value fixed in the calculations below.

Conversion from gallons to pounds certainly involves the volume V and the number 8.344, but do we multiply or divide? The way to solve this question is to *cancel the units you don't want*.

Suppose the volume V is exactly N cubic inches. Converting to gallons (this is review), write

$$V = \frac{N}{231} \text{ gal},$$

and get in the habit of writing gal, even if you already know you're working in gallons. Looking at the numerator and denominator of the weight density ρ , we see the unit for pounds in the numerator, and gallons in the denominator. Watch what happens when we multiply the weight density with the volume:

$$W = \rho \times V = 8.344 \frac{\text{lb}}{\text{gal}} \times \frac{N}{231} \text{ gal}$$

The only unit surviving cancellation is pounds, as we should expect for a weight calculation, hence why we call the product W . Cleaning up a bit, we have, for the weight of water in a column:

$$W = \frac{8.344}{231} \times N \text{ lb},$$

where N is the number of cubic inches in the volume. Said another way, 8.344/231 is the weight in pounds of one cubic inch of water.

Problem 9

Calculate the weight of one cubic foot of water.

Answer:

$$\begin{aligned} W &= \rho \times (1 \text{ ft}^3) = 8.344 \frac{\text{lb}}{\text{gal}} \left(12^3 \text{ in}^3 \right) \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) \\ &= \frac{8.344 \times 12^3}{231} \text{ lb} \approx 62.42 \text{ lb} \end{aligned}$$

Problem 10

How many cubic inches are in one pound of water?

Answer:

$$\begin{aligned} V &= \frac{W}{\rho} = 1 \text{ lb} \times \frac{1 \text{ gal}}{8.344 \text{ lb}} \left(\frac{231 \text{ in}^3}{1 \text{ gal}} \right) = \frac{231}{8.344} \text{ in}^3 \\ &\approx 27.68 \text{ in}^3 \end{aligned}$$

Problem 11

Calculate the weight of a water column with $H = 10$ ft and a circular cross section with $D = 4$ in.

Answer:

$$\begin{aligned} W_{\text{circ}} &= \rho \times V_{\text{circ}} = \frac{8.344 \text{ lb}}{1 \text{ gal}} H \times \left(\frac{\pi D^2}{4} \right) \\ &= \frac{8.344 \text{ lb}}{1 \text{ gal}} 120 \text{ in} \times \left(\frac{\pi 4^2 \text{ in}^2}{4} \right) \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) \\ &= \frac{8.344 \times 120 \times 4\pi}{231} \text{ lb} \approx 54.47 \text{ lb} \end{aligned}$$

Problem 12

Calculate the weight of a water column with $H = 10$ ft and a rectangular cross section with $X = Y = 4$ in.

Answer:

$$\begin{aligned} W_{\text{rect}} &= \rho \times V_{\text{rect}} = \frac{8.344 \text{ lb}}{1 \text{ gal}} H \times (X \times Y) \\ &= \frac{8.344 \text{ lb}}{1 \text{ gal}} 120 \text{ in} \times (4^2 \text{ in}^2) \left(\frac{1 \text{ gal}}{231 \text{ in}^3} \right) \\ &= \frac{8.344 \times 120 \times 16}{231} \text{ lb} \approx 69.35 \text{ lb} \end{aligned}$$

Problem 13

A cylindrical water column of height L and diameter D has the same weight as a rectangular water column with height Z and equal sides of length D . How much longer is L than Z ?

Answer:

$$\begin{aligned} W &= \rho \times V_{\text{cyl.}} = \rho \times V_{\text{box}} \\ V_{\text{cyl.}} &= V_{\text{box}} \\ L \times \left(\pi D^2 / 4 \right) &= Z \times (D \times D) \\ L &= \frac{4Z}{\pi} \rightarrow L - Z = Z \left(\frac{4}{\pi} - 1 \right) \end{aligned}$$

Problem 14

A ten-foot length of cast iron drain pipe has four-inch inner diameter and an outer diameter of 4.38 inches. Determine the volume of cast iron in cubic inches required to manufacture the pipe. (That is, how many one-inch cubes contain the same volume of material?)

Answer:

$$\begin{aligned} V &= 10 \text{ ft} \left(\frac{12 \text{ in}}{1 \text{ ft}} \right) \times \frac{\pi}{4} (4.38^2 - 4.00^2) \text{ in}^2 \\ &= \frac{120\pi}{4} (4.38^2 - 4.00^2) \text{ in}^3 \\ &\approx 300.1 \text{ in}^3 \end{aligned}$$

Problem 15

Take the weight density of cast iron to be 0.260 lb/in³. Convert this to pounds per gallon. How many times heavier is cast iron than an equal volume of water?

Answer:

$$\rho_{\text{C.I.}} = 0.260 \frac{\text{lb}}{\text{in}^3} \left(\frac{231 \text{ in}^3}{1 \text{ gal}} \right) \approx 60.1 \frac{\text{lb}}{\text{gal}}$$

$$\frac{\rho_{\text{C.I.}}}{\rho_{\text{water}}} = \frac{0.260 \times 231}{8.344} \approx 7.20$$

3.5 Pressure in a Column

By definition, *pressure* is equal to force divided by area. In the context of water columns, we can ask about the ‘weight of water’ felt under the surface at any height, including the bottom.

At the bottom of a water column, the weight of the water pressing down is represented by W , which qualifies as a force. For our straight columns of still water, dividing this by the cross-sectional area A gives

$$P_{\text{bottom}} - P_{\text{top}} = \frac{W}{A}.$$

This is the pressure increase through the water. When the top is open to the atmosphere, W/A is the bottom’s gauge pressure; its absolute pressure is $P_{\text{atm}} + W/A$.

Since the volume is given by $V = ZA$, eliminate A from the above to get

$$\Delta P = \frac{W}{V} Z,$$

where $\Delta P = P_{\text{bottom}} - P_{\text{top}}$. The quantity W/V is the total weight per total volume of water. This reduces to our adopted 8.344 pounds per 231 cubic inches of water. Thus if Z is expressed in inches, we get the pressure increase in pounds per square inch:

$$\Delta P = \left(\frac{8.344 \text{ lb}}{231 \text{ in}^3} \right) Z.$$

A popular formula for the above calculation involves providing the height in feet rather than inches. In this case - and we’ll leave the details of unit cancelation to the reader - we multiply the numerical factor by 12. Using H (in feet) in place of Z , we have

$$\Delta P = \left(\frac{12 \times 8.344 \text{ psi}}{231 \text{ ft}} \right) H.$$

The numerical prefactor works out to roughly 0.4335, in agreement with plumbing cheat sheets.

Problem 16

Suppose the gauge pressure at the base of a water column open to the atmosphere at the top is one pound per square inch. Calculate the height of the column in inches.

Answer:

$$1 \text{ psi} = \left(\frac{8.344 \text{ lb}}{231 \text{ in}^3} \right) Z$$

$$Z = 1 \times \frac{231}{8.344} \text{ in} \approx 27.68 \text{ in}$$

3.6 Atmospheric Pressure

The air around us has weight, and this weight exerts pressure on everything it touches. This pressure, called *atmospheric pressure*, is what supports the mercury in a barometer and the water in a straw. At sea level, atmospheric pressure is about 14.7 psi, meaning it exerts about 14.7 pounds-force per square inch of surface. The net force also depends on the pressure on the opposite side.

Problem 17

Convert 14.7 psi to pounds per square foot.

Answer:

$$14.7 \frac{\text{lb}}{\text{in}^2} = 14.7 \frac{\text{lb}}{\text{in}^2} \left(\frac{12 \text{ in}}{1 \text{ ft}} \right)^2$$

$$= 14.7 \times 12^2 \frac{\text{lb}}{\text{ft}^2} = 2116.8 \frac{\text{lb}}{\text{ft}^2}$$

Problem 18

When a water-filled tube is inverted with its top sealed and its lower end submerged in an open reservoir, atmospheric pressure on the reservoir supports a water column. Calculate the maximum height L of the water column above the reservoir surface, presuming the tube is at least as tall as L . For this ideal calculation, assume zero absolute pressure above the column and neglect water vapor pressure and capillary effects.

Answer:

$$\left(\frac{8.344 \text{ lb}}{231 \text{ in}^3} \right) L = 14.7 \frac{\text{lb}}{\text{in}^2}$$

$$L = \frac{231 \times 14.7}{8.344} \text{ in} \left(\frac{1 \text{ ft}}{12 \text{ in}} \right)$$

$$L \approx 33.91 \text{ ft}$$

Problem 19

Explain why the ideal static suction lift from an open reservoir is limited to about 34 ft at sea level.

Answer: A vacuum system lowers the pressure above the column. The pressure difference between the atmosphere acting on the reservoir and the space above the column supports the water’s weight:

$$\rho_{\text{water}} L = P_{\text{atm}} - P_{\text{top}}.$$

With zero absolute pressure at the top, the atmosphere can support a column of water about 34 ft tall at sea level. Real

water produces vapor, so an equilibrium water barometer has vapor pressure above its column even after air is removed. Trapped air also raises the top pressure. These effects reduce the supported height, and flow losses reduce practical pump suction lift further. Capillary effects are neglected here.

Problem 20

For these calculations, take the approximate weight density of mercury to be

$$\rho_{\text{mercury}} \approx 113.5 \frac{\text{lb}}{\text{gal}}.$$

Being much heavier than water, mercury allows for more compact construction of fluid columns, barometers, etc. If the gauge pressure at the base of a mercury column open to the atmosphere at the top is 1 psi, calculate the column height in inches.

Answer:

$$1 \text{ psi} = \left(\frac{113.5}{231} \frac{\text{lb}}{\text{in}^3} \right) Z$$

$$Z = 1 \times \frac{231}{113.5} \text{ in} \approx 2.0352 \text{ in}$$

Problem 21

If the atmosphere supports about 34 feet of water above the reservoir in the ideal top-sealed column, what height would it support in a similar mercury column? Again neglect vapor pressure and capillary effects.

Answer:

$$14.7 \text{ psi} = \left(\frac{113.5}{231} \frac{\text{lb}}{\text{in}^3} \right) Z$$

$$Z = 14.7 \times \frac{231}{113.5} \text{ in} \approx 29.918 \text{ in}$$

Problem 22

One inch is exactly 2.54 centimeters (cm), and there are 10 millimeters (mm) in one centimeter. Convert 29.918 inches to millimeters.

Answer:

$$29.918 \text{ in} = 29.918 \cancel{\text{in}} \left(\frac{2.54 \cancel{\text{cm}}}{1 \cancel{\text{in}}} \right) \left(\frac{10 \text{ mm}}{1 \cancel{\text{cm}}} \right)$$

$$= 29.918 \times 25.4 \text{ mm} \approx 759.9 \text{ mm}$$

3.7 Horizontal Column

Consider a cylindrical tank of volume $V = \pi R^2 L$, where $R = D/2$ is the radius and L is the length. The tank has flat ends and a level axis, and is filled partially with water to a depth h above the lowest point in the tank. For a given ratio h/R , what fraction of the tank's volume is filled with water? See Figure 3.

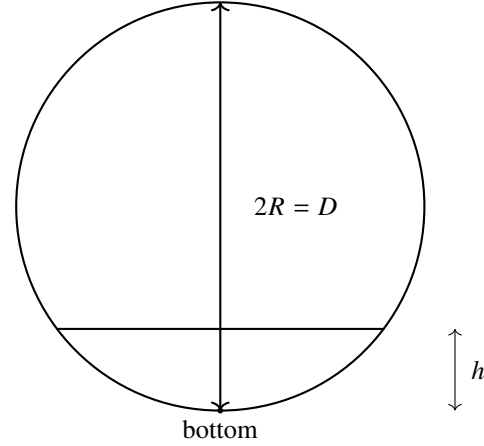


Figure 3. Cylindrical tank cross section showing vertical diameter $D = 2R$ and liquid level at height h above the bottom.

For convenience, redefine ‘down’ as pointing along the positive x -axis so the empty tank fills horizontally from the right. Placing the origin at the center of the circular cross section, the line defining the water’s surface has length

$$2y = 2R \sin(\theta),$$

where θ is measured in radians from the positive x -axis to the upper circle intersection. For the filled fraction, we can forget about the length of the tank entirely, because it cancels from the volume ratio.

Letting x represent the signed coordinate of the water’s surface relative to the center of the tank, then the x -coordinate obeys

$$x = R \cos(\theta),$$

along with

$$x + h = R.$$

We’ll need a formula for h/R , which we take from the above:

$$\frac{h}{R} = 1 - \frac{x}{R} = 1 - \cos(\theta)$$

Per our setup, the ratio h/R picks out a unique value for θ_* , for $0 \leq h/R \leq 2$, with $0 \leq \theta_* \leq \pi$. We use $x_* = R - h$ for the surface coordinate.

Setting up the area integral for the cross section of water occupying the tank, we begin with

$$A = -2 \int_R^{x_*} y \, dx,$$

which after using the trigonometric substitutions above becomes

$$A = 2R^2 \int_0^{\theta_*} \sin^2(\theta) \, d\theta,$$

simplifying further to

$$A = R^2 \left(\theta_* - \frac{1}{2} \sin(2\theta_*) \right).$$

Keep in mind that θ_* is related to the ratio h/R by

$$\theta_* = \arccos\left(1 - \frac{h}{R}\right) = \arccos\left(1 - \frac{2h}{D}\right).$$

The filled volume ratio is

$$\frac{V_{\text{water}}}{V} = \frac{A}{\pi R^2} = \frac{\theta_* - \frac{1}{2} \sin(2\theta_*)}{\pi}.$$

Evaluating these expressions, we generate the following results:

Ratio h/D	Angle θ_*	Vol. Rat.
0	0	0
0.05	0.45103	0.018693
0.1	0.64350	0.052044
0.15	0.79540	0.094060
0.2	0.92730	0.14238
0.25	1.0472	0.19550
0.3	1.1593	0.25232
0.35	1.2661	0.31192
0.4	1.3694	0.37353
0.45	1.4706	0.43644
0.5	$\pi/2$	0.5

For the case $\pi/2 \leq \theta_* \leq \pi$, the same relation applies:

$$\frac{h}{R} = 1 - \cos(\theta_*).$$

Continuing the list of θ_* -values, we find:

Ratio h/D	Angle θ_*	Vol. Rat.
0.55	1.6710	0.56356
0.6	1.7722	0.62647
0.65	1.8755	0.68808
0.7	1.9823	0.74768
0.75	2.0944	0.80450
0.8	2.2143	0.85762
0.85	2.3462	0.90594
0.9	2.4981	0.94796
0.95	2.6906	0.98131
1	π	1

Problem 23

A pipe laying on its side is partially filled with water such that $h/D = 25\%$. Use the information above to estimate the fraction of the pipe's volume that is occupied.

Answer:

$$h/D = 0.25 \rightarrow 19.55\% \text{ filled}$$

Problem 24

A pipe laying on its side is partially filled with water such that $h/D = 75\%$. Use the information above to estimate the fraction of the pipe's volume that is occupied.

Answer:

$$h/D = 0.75 \rightarrow 80.45\% \text{ filled}$$

4 Fixture Units

4.1 Review of Definitions

A term used heavily throughout the plumbing code is the *fixture unit*, which has a definition tailored for plumbers appearing in *Section 10.03: Definitions*:

Fixture Unit. *One cubic foot of water drained in a 1.25 in pipe over a period of one minute. One cubic foot of water is equal to 7.5 gal.*

The definition provided is alarmingly vague. Whether (or not) one cubic foot of water really drains through a 1.25 inch diameter pipe in exactly one minute is questionable. Needless to mention, one cubic foot is closer to 7.4805 gallons of liquid.

Dimensionality

Given the definition in CMR 10.03, one may expect that a fixture unit is a flow rate, perhaps measured in gallons per minute, and then perhaps multiplied (or divided?) by 1.25 somewhere, because surely the pipe diameter factors in. It turns out none of this is correct.

Browsing CMR 10 or comparable resources, one instead finds that fixture units are *not* measured in physical units, but are instead always dimensionless scale factors like 3, π , or 1000.

4.2 Alternate Definitions

Massachusetts Plumbing Code (CMR 10.03)

Also found in *Section 10.03: Definitions* is the definition of *load factor*, which reads:

Load Factor. *The percentage of the total connected fixture unit flow which is likely to occur at any point in the drainage system. It varies with the type of occupancy, the total flow unit above this point being considered, and with the probability factor of simultaneous use.*

This definition is a slight improvement over the previous one by alluding to likelihood of occurrence and type of occupancy.

Sadly, the terms ‘probability’ and ‘load factor’ appear nowhere else in CMR 10. There is, of course, the suspiciously-related term ‘demand factor’ used in CMR 10.14, but this term is not defined in 10.03. A similar comment applies to the term ‘factor value’. That is, ‘factor value’ seems to be related, is used, but is never defined in CMR 10.03.

Uniform Plumbing Code (UPC)

Reaching for the *Uniform Plumbing Code, IAPMO/ANSI 1 - 2021*, one finds a dignified but unhelpful word salad explaining the fixture unit:

Fixture Unit. *A quantity in terms of which the load-producing effects on the plumbing system of different kinds of plumbing fixtures are expressed on some arbitrarily chosen scale.*

International Plumbing Code (IPC)

We finally encounter a sensible definition of the fixture unit in the *International Plumbing Code (IPC)* (e.g., 2021 edition), which reads:

Drainage Fixture Unit. *A measure of the probable discharge into the drainage system by various types of plumbing fixtures. The drainage fixture-unit value for a particular fixture depends on its volume rate of drainage discharge, on the time duration of a single drainage operation and on the average time between successive operations.*

Mometrix Media

A set of flash cards produced by Mometrix Media offers the following comment on fixture units:

A fixture unit is a unit used to measure the rate of water flow, equal to one cubic foot of water (roughly 7.48 gallons) per minute.

Claiming that the fixture unit is *equal* to one (physical) cubic foot of water per (real-time) minute is almost as bad as what we find in CMR 10.

One can speculate as to why the definition of the fixture unit varies so vividly per authority. Regardless of this, any literal understanding of the matter will remain elusive if plumbing codes are the only resource.

The Plan

We’ve racked up plenty of bad karma by slaughtering the definition of the fixture unit, and the intent here is not to solve the problems with the definition stated in CMR 10 or other publications. Instead, the plan is to take a first-principles approach using probability theory in the same way as done by the inventor of the fixture unit, Roy B. Hunter, in the years leading to 1940.

We start with a homemade exercise called the **Valve and Tank Problem**, which is informed by a mixture of real data and more-or-less made up numbers corresponding to likelihood of occurrence, type of occupancy, etc., of certain plumbing fixtures.

Next, we pursue **Hunter’s Calculation** to once-and-for-all force an understanding of the fixture unit. Such an effort also yields the so-called *Hunter’s curve*, which is the source of the various ‘gallons per minute versus fixture unit’ tables occurring in the myriad of plumbing resources,

including CMR 10. **You can skip the gritty calculations if math isn't your thing.** or

Fixture unit values tend to change over time and location, however the work that follows will readily generalize to suit any fixture parameters. Data contemporary to the 1940s is used to ensure we're on track with the original work of R. B. Hunter.

4.3 Valve and Tank Problem

Two devices, or *fixtures* in American plumbing systems are the (i) *flush valve*, and (ii) the *flush tank*. The flush valve conveys 4 gallons of water over a period of 9 seconds.¹ The flush tank conveys 4 gallons in 60 seconds. Assume that all flush valves and flush tanks are used six times per hour on average. Assume steady use, independent operating states, constant flow during each operation, and no overlapping operations on the same fixture. The tank's 60 seconds refers to refilling from the supply.

If a certain building has $V = 20$ flush valves and $T = 30$ flush tanks, use only the information provided to (i) estimate the combined number of devices j being used simultaneously. (ii) Calculate the probability $P(j)$ of any j occurring and check that the estimate for j is correct. (iii) Calculate the probability that zero devices are in use at a given moment. (iv) Determine the smallest integer k for which $\Pr(j > k) \leq 1\%$. (v) Calculate the smallest flow threshold d for which $\Pr(D > d) \leq 1\%$.

Per hour (3600 seconds), a flush valve is operating for an average of 54 seconds. Similarly, a flush tank operates for 360 seconds. At a given moment, there is a

$$p_v = \frac{54}{3600} = 0.015$$

probability that a given flush valve is operating, and a

$$p_t = \frac{360}{3600} = 0.1$$

probability that a flush tank is operating.

Modal Analysis

Let x_v denote the number of flush valves in use simultaneously, and let x_t be the number of flush tanks being used such that

$$j = x_v + x_t$$

at a given moment.

Modeling each fixture as a weighted coin, we know from the binomial distribution that the most probable values for x_v , x_t are the respective modes

$$\begin{aligned} x_v^* &= \lfloor (V+1)p_v \rfloor \\ x_t^* &= \lfloor (T+1)p_t \rfloor, \end{aligned}$$

$$x_v^* = \lfloor (20+1)(0.015) \rfloor = 0$$

$$x_t^* = \lfloor (30+1)(0.1) \rfloor = 3.$$

If $(n+1)p$ is an integer, both that integer and the preceding integer are modes, for $0 < p < 1$.

The combined mode j^* must be found from the combined distribution. Using the numbers on hand, the calculation below confirms

$$j^* = 3.$$

That is, we expect about three devices to be conveying water at a given moment. The total mode is essentially dominated by x_t^* .

In terms of x_v , x_t , the water demand rate $D(x_v, x_t)$ is given by

$$D(x_v, x_t) = x_v \left(\frac{4 \text{ gal}}{9 \text{ s}} \right) + x_t \left(\frac{4 \text{ gal}}{60 \text{ s}} \right).$$

Using $j = 3$, it follows that x_v can take on any value 0, 1, 2, 3. Thus:

$$D(0, 3) = 0.2 \text{ gal/s}$$

$$D(1, 2) = (0.44\bar{4} + 0.13\bar{3}) \text{ gal/s} = 0.57\bar{7} \text{ gal/s}$$

$$D(2, 1) = (0.88\bar{8} + 0.06\bar{6}) \text{ gal/s} = 0.95\bar{5} \text{ gal/s}$$

$$D(3, 0) = 1.3\bar{3} \text{ gal/s}$$

To make use of the above information, recall from the values of x_v^* , x_t^* that (0, 3) (zero flush valves in use, three flush tanks in use) is the most likely configuration at a given moment, and the typical water demand is estimated at 0.2 gal/s, or 12 gallons per minute. The mean demand is different: $(0.3)(80/3) + (3)(4) = 20$ gallons per minute.

Of course, we don't want to design based on typical use. It's much better to anticipate the worst-probable case, which is not the worst *possible* case. (To design based on the worst possible case scenario is inefficient, costly, or worse.)

Probabilistic Analysis

The probability that there are x_v flush valves in use is given by the binomial distribution:

$$P_v(x_v) = \binom{V}{x_v} (1-p_v)^{V-x_v} p_v^{x_v}$$

Also in terms of x_v , we write for the flush tank:

$$P_t(j - x_v) = \binom{T}{j - x_v} (1-p_t)^{T-(j-x_v)} p_t^{j-x_v}$$

¹Figures gathered from PDH Course M126, *Sizing Plumbing Water System*. A. Bhatia. 2020. www.PDHonline.org

The total probability is the convolution of the two above distributions:

$$P(j) = \sum_{x_v=\max(0,j-T)}^{\min(j,V)} P_v(x_v) \cdot P_t(j-x_v)$$

Using $j = 3$, the above probability is

$$P(3) = \sum_{x_v=0}^3 P_v(x_v) \cdot P_t(j-x_v),$$

where:

$$P_v(x_v) = \binom{20}{x_v} (1-0.015)^{20-x_v} (0.015)^{x_v}$$

$$P_t(j-x_v) = \binom{30}{3-x_v} (1-0.1)^{30-(3-x_v)} (0.1)^{3-x_v}$$

Evaluating $P(3)$ is quite a chore. For $x_v = 0$, we have:

$$P_v(0) = \binom{20}{0} (1-0.015)^{20} (0.015)^0 \approx 0.7391$$

$$P_t(3) = \binom{30}{3} (1-0.1)^{27} (0.1)^3 \approx 0.2361$$

$$P_v(0) \cdot P_t(3) \approx 0.1745$$

Continuing for $x_v = 1$:

$$P_v(1) = \binom{20}{1} (1-0.015)^{19} (0.015)^1 \approx 0.2251$$

$$P_t(2) = \binom{30}{2} (1-0.1)^{28} (0.1)^2 \approx 0.2277$$

$$P_v(1) \cdot P_t(2) \approx 0.05125$$

Continuing for $x_v = 2$:

$$P_v(2) = \binom{20}{2} (1-0.015)^{18} (0.015)^2 \approx 0.03257$$

$$P_t(1) = \binom{30}{1} (1-0.1)^{29} (0.1)^1 \approx 0.1413$$

$$P_v(2) \cdot P_t(1) \approx 0.004602$$

Continuing for $x_v = 3$:

$$P_v(3) = \binom{20}{3} (1-0.015)^{17} (0.015)^3 \approx 0.002976$$

$$P_t(0) = \binom{30}{0} (1-0.1)^{30} (0.1)^0 \approx 0.04239$$

$$P_v(3) \cdot P_t(0) \approx 0.0001261$$

The total probability that any three of the 20 + 30 flush valves and flush tanks are in simultaneous use is the sum of the above convolutions:

$$P(3) \approx 0.2305 \approx 23.05\%$$

Returning briefly to the issue of water demand, compare each convolution $P_v(x_v) \cdot P_t(j-x_v)$ to see the figure 0.1745 dominating its siblings, thus (0, 3) is the most likely configuration in accordance with our estimate of $j^* = 3$.

We still need to establish that $P(3)$ is greater than all other $P(j)$. To study the $j = 2$ case, we need

$$P(2) = \sum_{x_v=0}^2 P_v(x_v) \cdot P_t(j-x_v),$$

or:

$$P(2) = P_v(0) \cdot P_t(2) + P_v(1) \cdot P_t(1) + P_v(2) \cdot P_t(0)$$

Using the figures calculated above, we learn

$$P(2) \approx 0.1683 + 0.03181 + 0.001381 \approx 0.2015 = 20.15\%.$$

The $j = 1$ case is also done easily, as

$$P(1) = P_v(0) \cdot P_t(1) + P_v(1) \cdot P_t(0)$$

readily computes to

$$P(1) \approx 0.1044 + 0.009543 \approx 0.1140 \approx 11.40\%.$$

The $j = 0$ case is trivial from the information on hand, coming out to

$$P(0) \approx (0.7391) (0.04239) \approx 0.03133 \approx 3.133\%.$$

Reading this result backward, we see there is a 96.87% chance that at least one device is operating at a given moment.

Technically, we need to also check all additional $P(j)$ up to $j = 50$. This is best left to a machine, so we'll do one more case by hand, namely $j = 4$. For this, we need

$$P(4) = P_v(0) \cdot P_t(4) + P_v(1) \cdot P_t(3) + P_v(2) \cdot P_t(2) + P_v(3) \cdot P_t(1) + P_v(4) \cdot P_t(0).$$

Most of these figures were calculated above, with the new members being:

$$P_v(4) = \binom{20}{4} (1-0.015)^{16} (0.015)^4 \approx 0.0001926$$

$$P_t(4) = \binom{30}{4} (1-0.1)^{26} (0.1)^4 \approx 0.1771$$

Turning the crank, one finds

$$P(4) \approx 0.1309 + 0.05315 + 0.007414 + 0.0004205 + .000008164,$$

or

$$P(4) \approx 0.1919 \approx 19.19\% .$$

To summarize, we found

$$P(0) \approx 3.133\%$$

$$P(1) \approx 11.40\%$$

$$P(2) \approx 20.15\%$$

$$P(3) \approx 23.05\%$$

$$P(4) \approx 19.19\% ,$$

which is maximal at $j = 3$. Checking the remaining values by computer confirms that all subsequent $P(j > 4)$ are less than $P(3)$.

Summing the unrounded probabilities above, we conclude that there is a 76.91% chance that any number from zero to four devices are in use simultaneously. This means there is a 23.09% chance that any number $5 \leq j \leq 50$ devices are in use simultaneously.

Summing the upper tail of $P(j)$, we find

$$\Pr(j > 7) \approx 1.4547\%, \quad \Pr(j > 8) \approx 0.4341\% ,$$

thus the smallest count threshold is

$$k = 8 .$$

This count does not specify the mixture of valves and tanks.

For a final flow rate we must check all combinations of valves and tanks. In gallons per minute,

$$D(a, b) = \frac{80}{3}a + 4b .$$

Summing the probabilities of configurations above a trial flow d , we find

$$\Pr(D > d) = \sum_{\substack{0 \leq a \leq 20, 0 \leq b \leq 30 \\ (80/3)a + 4b > d}} P_v(a)P_t(b) .$$

Turning the crank for all $21 \times 31 = 651$ configurations gives

$$d = 69\frac{1}{3} \text{ gal/min} ,$$

with an exceedance probability of 0.8914%. At the preceding possible flow, 68 gallons per minute, the exceedance probability is 1.4680%.

Design Factor

To reiterate the last step, one requires $\Pr(j > k) \leq 1\%$, not $P(k) = 1\%$. The special value k is also called a *design factor*. For this problem, there is about a 0.4341% chance that more than 8 of the 50 fixtures are operating

simultaneously. Different flow rates require the separate demand calculation above. These probabilities refer to a randomly chosen moment under the stated assumptions, not to whether an exceedance happens at least once during a day.

4.4 Hunter's Calculation

While adequate, the above calculation is admittedly too detailed for application in the field, especially when there are multiple types of plumbing devices in the system. We will use exact integer thresholds for the binomial model. Hunter's published curves used approximations and a rounded flush-valve flow of 27 gpm; our calculations retain 80/3 gpm.²

To work toward something simpler, separately consider a (i) flush valve, (ii) flush tank, (iii) bathtub having the following characteristics³:

- The flush valve conveys 4 gallons over an interval of 9 seconds per use, and is used once every 5 minutes (300 s, twelve uses per hour).
- The flush tank conveys 4 gallons over an interval of 60 seconds per use, and is used once every 5 minutes (300 s, twelve uses per hour).
- A bathtub requires 16 gallons over an interval of 120 seconds, and is used once every 30 minutes (1800 s).

From these, we find that the flush valve operates a total of 108 seconds for every 3600. Thus the probability of any given flush valve being in use is

$$p_v = \frac{108}{3600} = 0.03 .$$

Similarly, the flush tank has

$$p_t = \frac{720}{3600} = 0.2 ,$$

and finally for the bathtub:

$$p_b = \frac{120}{1800} \approx 0.06667$$

Then, one can immediately write the probability that x_v flush valves are in use out of V total valves:

$$P_v(x_v, V) = \binom{V}{x_v} (1 - p_v)^{V - x_v} p_v^{x_v}$$

From each value V we can derive a most-likely number of valves x_v^* in simultaneous use, along with a design factor k_v such that $\sum_{x_v=k_v+1}^V P_v(x_v, V) \leq 1\%$, choosing the smallest

²Hunter, BMS 65, printed pages 7–8 and 11–15. The design criterion concerns the upper tail, not a single probability equal to 1%.

³National Bureau of Standards Report: BMS 65 by Late Dr. R. B. Hunter (1940)

such integer k_v . The very same can be said for flush tanks by switching indices $v \rightarrow t$, $V \rightarrow T$, leading to

$$P_t(x_t, T) = \binom{T}{x_t} (1 - p_t)^{T-x_t} p_t^{x_t},$$

and then switching indices to b , B for bathtubs, we have

$$P_b(x_b, B) = \binom{B}{x_b} (1 - p_b)^{B-x_b} p_b^{x_b}.$$

Now we must find a design factor for each probability considered. To proceed, choose $V = T = B = 25$ and use a computer to find:

- $\sum_{x_v=k_v+1}^{25} P_v(x_v, 25) \leq 1\%$ first holds at $k_v = 3$
- $\sum_{x_t=k_t+1}^{25} P_t(x_t, 25) \leq 1\%$ first holds at $k_t = 10$
- $\sum_{x_b=k_b+1}^{25} P_b(x_b, 25) \leq 1\%$ first holds at $k_b = 5$

Using each k -value, calculate the total water demand for each case of 25 fixtures:

$$D_v(k_v) = 3 \left(\frac{4 \text{ gal}}{9 \text{ s}} \right) \approx 80.00 \frac{\text{gal}}{\text{min}}$$

$$D_t(k_t) = 10 \left(\frac{4 \text{ gal}}{60 \text{ s}} \right) \approx 40.00 \frac{\text{gal}}{\text{min}}$$

$$D_b(k_b) = 5 \left(\frac{8 \text{ gal}}{60 \text{ s}} \right) \approx 40.00 \frac{\text{gal}}{\text{min}}$$

Repeating for $V = T = B = 50$, find:

- $\sum_{x_v=k_v+1}^{50} P_v(x_v, 50) \leq 1\%$ first holds at $k_v = 5$
- $\sum_{x_t=k_t+1}^{50} P_t(x_t, 50) \leq 1\%$ first holds at $k_t = 17$
- $\sum_{x_b=k_b+1}^{50} P_b(x_b, 50) \leq 1\%$ first holds at $k_b = 8$

Then, for 50 fixtures:

$$D_v(k_v) = 5 \left(\frac{4 \text{ gal}}{9 \text{ s}} \right) \approx 133.33 \frac{\text{gal}}{\text{min}}$$

$$D_t(k_t) = 17 \left(\frac{4 \text{ gal}}{60 \text{ s}} \right) \approx 68.00 \frac{\text{gal}}{\text{min}}$$

$$D_b(k_b) = 8 \left(\frac{8 \text{ gal}}{60 \text{ s}} \right) \approx 64.00 \frac{\text{gal}}{\text{min}}$$

Repeating again for $V = T = B = 75$, find:

- $\sum_{x_v=k_v+1}^{75} P_v(x_v, 75) \leq 1\%$ first holds at $k_v = 6$
- $\sum_{x_t=k_t+1}^{75} P_t(x_t, 75) \leq 1\%$ first holds at $k_t = 23$
- $\sum_{x_b=k_b+1}^{75} P_b(x_b, 75) \leq 1\%$ first holds at $k_b = 11$

Then, for 75 fixtures:

$$D_v(k_v) = 6 \left(\frac{4 \text{ gal}}{9 \text{ s}} \right) \approx 160.00 \frac{\text{gal}}{\text{min}}$$

$$D_t(k_t) = 23 \left(\frac{4 \text{ gal}}{60 \text{ s}} \right) \approx 92.00 \frac{\text{gal}}{\text{min}}$$

$$D_b(k_b) = 11 \left(\frac{8 \text{ gal}}{60 \text{ s}} \right) \approx 88.00 \frac{\text{gal}}{\text{min}}$$

Repeating once more for $V = T = B = 100$, find:

- $\sum_{x_v=k_v+1}^{100} P_v(x_v, 100) \leq 1\%$ first holds at $k_v = 8$
- $\sum_{x_t=k_t+1}^{100} P_t(x_t, 100) \leq 1\%$ first holds at $k_t = 30$
- $\sum_{x_b=k_b+1}^{100} P_b(x_b, 100) \leq 1\%$ first holds at $k_b = 13$

Then, for 100 fixtures:

$$D_v(k_v) = 8 \left(\frac{4 \text{ gal}}{9 \text{ s}} \right) \approx 213.33 \frac{\text{gal}}{\text{min}}$$

$$D_t(k_t) = 30 \left(\frac{4 \text{ gal}}{60 \text{ s}} \right) \approx 120.00 \frac{\text{gal}}{\text{min}}$$

$$D_b(k_b) = 13 \left(\frac{8 \text{ gal}}{60 \text{ s}} \right) \approx 104.00 \frac{\text{gal}}{\text{min}}$$

4.5 Fixture Unit Defined

After suffering (or skipping) the above analysis, it would be efficient to restate all results in table form with assistance from a computer or programmable calculator to crunch the numbers.

Fixture Count v.s. GPM

In the following table, the first column holds a number of fixtures, and the remaining three columns hold the gallons-per-minute (gpm) flow rates through the respective fixtures. This is an extended summary of the integer-threshold calculation above, with flow rates rounded to two decimal places:

Fixture (count)	Valve (gpm)	Tank (gpm)	Bath (gpm)
5	26.67	12.00	16.00
10	53.33	20.00	24.00
15	53.33	28.00	32.00
20	80.00	32.00	32.00
25	80.00	40.00	40.00
50	133.33	68.00	64.00
75	160.00	92.00	88.00
100	213.33	120.00	104.00
125	240.00	144.00	120.00
150	266.67	168.00	144.00
175	293.33	192.00	160.00
200	320.00	216.00	176.00
250	373.33	260.00	208.00
300	426.67	308.00	248.00
350	506.67	352.00	280.00

GPM v.s. Fixture Count

One can derive a similar table with a fixed gpm threshold and a variable number of fixtures. Aiming for 50 gal/min, taking the smallest fixture counts whose design demands reach or exceed it, we find (i) $V = 6$ yields $D_v = 53.33$ gal/min, (ii) $T = 34$ yields $D_t = 52.00$ gal/min, (iii) $B = 37$ yields $D_b = 56.00$ gal/min. Together, we jot the ratio 6 : 34 : 37 for flush valves, flush tanks, and bathtubs, respectively. Repeating this for incrementing gpm rates yields the following:

Demand (gpm)	Valve (count)	Tank (count)	Bath (count)
50	6	34	37
100	29	80	95
150	62	133	160
200	99	183	228
250	141	239	311
300	184	292	384

The relationship between the flow rate in gallons per minute and total fixture count is more-or-less linear for each fixture type in the domain 150 gpm to 300 gpm, thus we will toss out any data outside this window.

GPM v.s. Flush Valve Ratio

The next move is to express all fixtures in terms of the flush valve as Hunter did. Going across each row, divide the respective numbers of flush tanks and bathtubs by the number of flush valves. Also divide the number of flush valves by itself to attain 1. Doing so yields:

Demand (gpm)	Valve (ratio)	Tank (ratio)	Bath (ratio)
150	1	2.145	2.581
200	1	1.848	2.303
250	1	1.695	2.206
300	1	1.587	2.087
(Average:)	1	1.819	2.294

Interpreting the bottom row, we find the average count ratio 1 : 1.819 : 2.294 for valves, tanks, and bathtubs over this range. The weights run inversely to these counts. Assigning a valve weight of 10, calculate $10V/T$ and $10V/B$ in each row, then average to find 5.57 for tanks and 4.39 for baths. These are approximate comparisons, not exact equivalences for every group size.

Hunter's historical weights 10, 5, 4, which we retain for comparison with his curves, are the respective *fixture units*, abbreviated FU, for the flush valve, flush tank, and bathtub, respectively. They are approximate historical weights, not the rounded values of our new calculation.

Better Definition

We have illustrated that **any plumbing fixture is characterized by a fixture-unit value, a dimensionless number informed by the fixture's volume through-rate and probability/duration of use. The instantaneous gpm demand is the sum of the flows operating at that moment. The design demand is not generally the sum of the individual design demands. Rather, count the total fixture units and use the matching Hunter's curve (or equivalent chart) to estimate total gpm demand.**

Corollary

Equal average water supply and waste drainage do not imply equal peak flow rates. A flush tank refills slowly and discharges its stored water much faster. Thus the supply calculation does not establish the drainage load.

For this reason, it's prudent to differentiate between water supply fixture units (WSFU) versus waste drainage fixture units (DFU). Fixture unit values tend to vary in each regime, as the conditions and contents of a given pipe may factor into that pipe's ability to pass volume through the system.

Different loading conditions require separate ratings, even where the same term 'fixture unit' is used. CMR 10.14 offers the term 'factor value' for water supply, however this term is not defined in CMR 10.03. Meanwhile, 'fixture unit' is seemingly reserved for waste and drainage.

Forensics

Reviewing the definitions that brought us here, it appears that *International Plumbing Code, 2021 edition*, gives a

definition consistent with the loading factors discussed here, but also skimps elaboration on what ‘kind’ of measure to which the definition alludes.

Meanwhile, in *IAMPO/ANSI I - 2021, Uniform Plumbing Code*, the allusion to ‘some arbitrarily chosen scale’ in should be clear at this point. The scale sets the relative weights; Hunter’s curve relates their total to an estimated demand (See Figure 5).

What are we to do with the definition listed in CMR 10? Back to flush valves... Suppose a valve conveys 1.5 gallons over 6 seconds. Its operating flow is 0.25 gallons per second, or 15 gallons per minute. If it is assigned 6 fixture units, division gives 2.5 gpm per assigned unit for that example. This does not establish a universal conversion, nor does it reproduce CMR 10.03’s definition.

Note, of course, that the 1.25 inch diameter pipe mentioned in CMR 10 never entered the analysis, so this supply calculation does not explain its role in that drainage definition.

4.6 Hunter’s Curve

Fixture unit calculations were originally carried out by Roy B. Hunter in the years leading to 1940 and published by the *National Bureau of Standards Report: BMS 65*.

Using 10, 5, 4 as scale factors, recast the ‘gpm vs. count’ table by multiplying all *V* by 10, all *T* by 5, and all *B* by 4. This produces an equivalent table with fixture counts replaced by fixture units:

Demand	Valve	Tank	Bath
(gpm)	(FU)	(FU)	(FU)
150	620	665	640
200	990	915	912
250	1410	1195	1244
300	1840	1460	1536

The table above uses our integer thresholds. Hunter’s historical calculation is shown in Figure 4. Using the Figure, Hunter reasoned:

‘...the error made by using curve 2 for both flush tanks and bathtubs for any number of either up to 300 would be small. Also, the demand load relative to the number of fixture units may be approximately represented in this range by a smoother curve drawn above the two probability curves and merged with curve 1 as shown by the broken line in [the] Figure...’

That is, curve 2 and curve 3 are essentially interchangeable before the broken line, and then the broken line takes over for curves 2 and 3 until joining curve 1, giving rise to Figure 5. The result is called called *Hunter’s Curve*.

Demand vs Fixture Units

Finally, we summarize our calculation in fixture units using the tables that follow. The Valve column uses [FU/10] valves; the Tank column uses [FU/5] tanks. The ceiling rounds up to a whole fixture where necessary. Each column gives the separate group’s 99% demand threshold. These are calculated tables, not readings of Hunter’s smoothed curve or exact demands for mixed groups.

Demand (Load)	Valve	Tank
(FU)	(gpm)	(gpm)
10	26.67	8.00
20	26.67	12.00
30	26.67	16.00
40	26.67	20.00
50	26.67	20.00
60	53.33	24.00
70	53.33	28.00
80	53.33	28.00
90	53.33	32.00

The same calculation continues in the next table.

Demand (Load)	Valve	Tank
(FU)	(gpm)	(gpm)
100	53.33	32.00
140	53.33	44.00
180	80.00	52.00
200	80.00	56.00
250	80.00	68.00
300	106.67	80.00
400	106.67	100.00
500	133.33	120.00
750	160.00	168.00

The separately calculated columns remain distinct above 1000 fixture units.

Demand (Load)	Valve	Tank
(FU)	(gpm)	(gpm)
1000	213.33	216.00
1250	240.00	260.00
1500	266.67	308.00
1750	293.33	352.00
2000	320.00	396.00
2500	373.33	484.00
3000	426.67	572.00
4000	560.00	748.00
5000	666.67	920.00

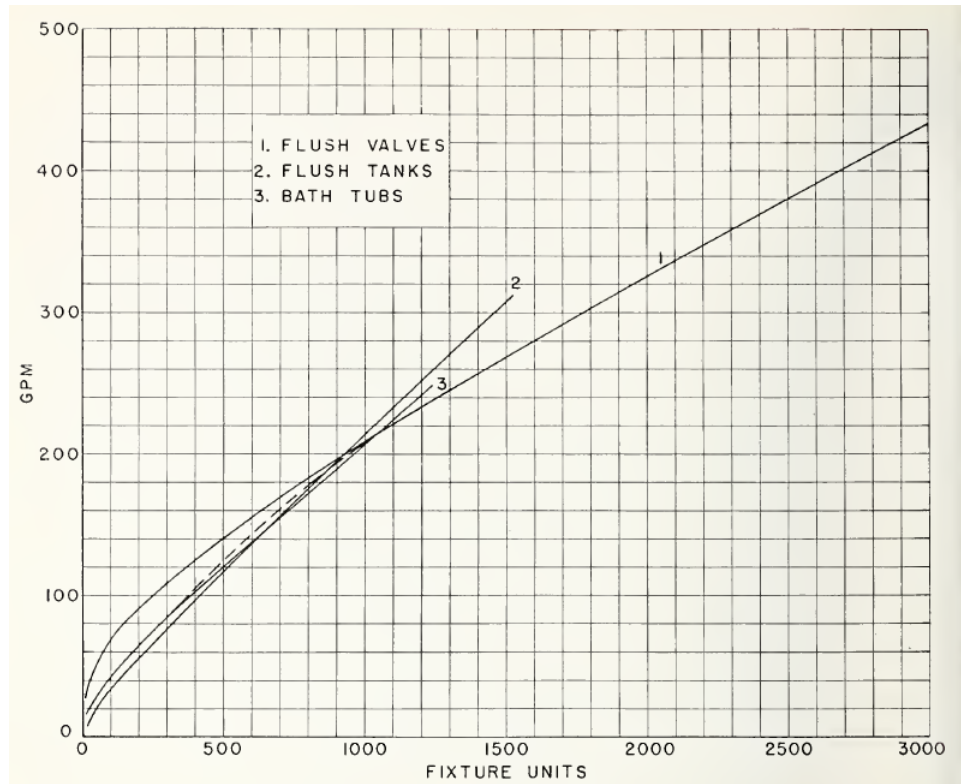


Figure 4. Gallons per minute versus fixture unit count for flush valves, flush tanks, and bathtubs. (*National Bureau of Standards Report: BMS 65, 1940*)

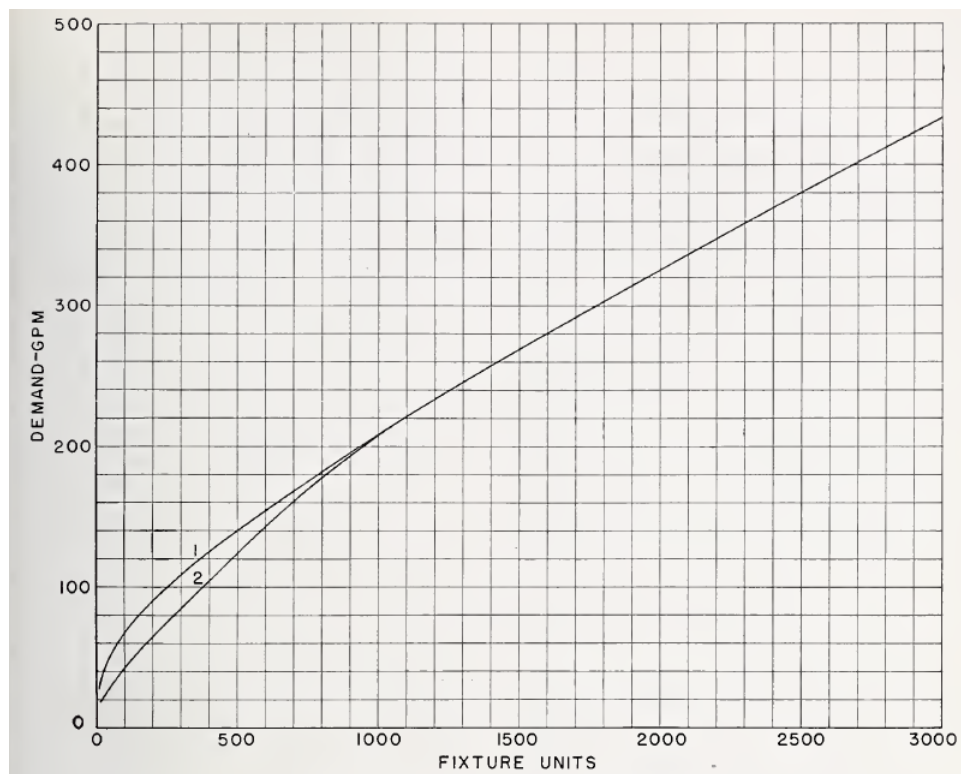


Figure 5. Hunter's Curve. (*National Bureau of Standards Report: BMS 65, 1940*)

5 Traps and Cleanouts

Traps prevent the passage of sewer gases by maintaining a liquid seal while allowing wastewater to drain. Cleanouts provide access for clearing drainage piping. The main requirements are in 248 CMR 10.08. Additional seal-protection requirements appear in 10.02(9), and floor/trough drain requirements appear in 10.10(6). All code references below are to the December 8, 2023 version of 248 CMR 10.00. (10.03, definition of *Trap*; 10.02(7), (9).)

5.1 Five Parts

For a typical P-trap, five useful terms are inlet, seal, dip, weir, and outlet. These describe the trap's geometry and operation; the code does not prescribe a universal list of five separate parts for every trap design.

1. **Inlet.** The point at which wastewater from a fixture enters the trap and is directed into the trap body.
2. **Seal.** The retained water forming the liquid barrier between the fixture and the sanitary drainage system. The code defines *trap seal* as the vertical distance between the crown weir and the top of the dip. (10.03, definitions of *Trap* and *Trap Seal*.)
3. **Dip.** The low bend of the trap. For seal-depth measurement, use the *top of the dip*: the upper inside surface of that bend, where a falling water level would first open an air passage through the trap. Do not measure to the bottom of the water-filled bend. (10.03, definition of *Trap Seal*; 10.08(2)(e), Example 3.)
4. **Weir.** The crest on the outlet side over which water flows to leave the trap. It establishes the standing water level after flow stops and pressures equalize. The vertical distance from the crown weir down to the top of the dip is the seal depth. (10.03, definition of *Trap Seal*; 10.08(2)(e), Example 3.)
5. **Outlet.** The point at which water leaves the trap and flows into the trap arm or waste line. The code defines the trap arm as the portion of the fixture drain or waste drain between the trap and its vent. (10.03, definition of *Trap Arm*.)

Trap geometry varies, and a liquid seal alone does not establish that a design is permitted. Full S-traps are prohibited. Fixture traps must be self-scouring; interior partitions are allowed only where the trap is integral with the fixture. A drum trap should not be treated as a generally interchangeable substitute for a P-trap. (10.08(2)(c)4.–5.; 10.08(2)(d)1.)

5.2 Trap Requirements

1. **Separate trapping.** Individual fixtures must have water-seal traps as close as possible to their outlets. Exceptions cover fixtures with integral traps, qualifying combination fixtures, qualifying groups of up to three adjacent sinks or lavatories, and the listed domestic dishwasher connections. The shared-trap arrangements have limits on compartment depth, outlet spacing, and trap location. (10.08(2)(a)1.a.i.–iv.)
2. **Vertical distance.** The vertical distance from the fixture outlet to the trap weir must not exceed 24 inches. (10.08(2)(a)1.b.)
3. **Size.** The trap must drain the fixture rapidly, meet the minimum size in Table 1, and be the same pipe size as the drain into which it discharges. For example, the table specifies a minimum 1½-inch trap for a common lavatory or bathtub, and a 2-inch trap for a shower stall, floor drain, or clothes washing machine connection. (10.08(2)(b)1.–2., Table 1.)
4. **Seal depth.** Each fixture trap must have a liquid seal at least 2 inches and not more than 4 inches deep, except where special conditions require a deeper seal. Floor/trough drains have a separate minimum of 3 inches. (10.08(2)(e); 10.10(6)(a).)
5. **Pressure protection.** The drainage and vent arrangement must protect the seal so that the trap is never subjected to a pressure differential greater than 1 inch of water. Venting does not replenish water lost through evaporation or repair a leaking trap. (10.08(2)(e); 10.02(9).)
6. **Setting.** Traps must be set level with respect to their water seals and protected from freezing wherever necessary. (10.08(2)(f).)
7. **Prohibited designs.** The code prohibits traps that depend on moving parts for their seals, bell traps, crown-vented traps, separate fixture traps that depend on interior partitions, and full S-traps. (10.08(2)(c)1.–5.)
8. **Materials and joints.** Fixture traps must meet the material requirements referenced by 10.08(1). Exposed traps made of copper-alloy tubing must be at least 17 gauge. Slip or ground joints forming part of a trap must meet 10.07(6). (10.08(1); 10.08(2)(d)2.)
9. **Cleaning the trap.** A fixture trap generally needs an accessible cleanout plug of ample size, protected by the water seal. Exceptions apply when the seal is readily accessible in an integral or combined fixture trap, or a portion of the trap is readily removable for cleaning. For floor-outlet and similar fixtures,

including tubs and showers, where a trap cleanout would be inaccessible, a cleanout must be installed at the nearest accessible location. (10.08(2)(d)3., Exceptions a.–b.)

10. **Building and running traps.** These are generally prohibited unless the Inspector deems them necessary. The code provides a freezing-protection exception and separate rules for open parking garages. An installed building trap needs an accessible cleanout and a relieving vent or fresh-air intake. (10.08(2)(g)1.–3.)

5.3 SLAMOBEC

Trap seals may be compromised by the eight causes summarized by **SLAMOBEC**. All eight are listed in 10.02(9). The descriptions below explain the physical mechanisms; the code names the causes and requires seal protection. Some mechanisms overlap, particularly aspiration and induced siphonage.

1. **Siphonage.** Negative pressure can draw water out of the trap. Self-siphonage results from the fixture's own discharge; induced siphonage results from discharge elsewhere in the drainage system. (10.02(9); 10.08(2)(e).)
2. **Leakage.** Cracks, defective joints, or loose plugs below the retained water level may allow the seal water to escape. A leak above that level may release gas without draining the seal. (Seal-protection requirement: 10.02(9).)
3. **Aspiration.** Flow past a branch connection can entrain air and lower pressure in the branch, drawing water from the trap. This can produce induced siphonage; correct venting limits the pressure difference. (10.02(9); 10.08(2)(e).)
4. **Momentum.** The inertia of the discharging water can carry seal water out of the trap as the flow ends. Trap geometry and discharge conditions matter; excessive trap-arm length or slope is not the definition of momentum loss. (10.02(9); 10.08(2)(e).)
5. **Oscillation.** Fluctuating pressure can make the seal water move back and forth. If water spills into the drain during these movements, the remaining seal becomes shallower. Oscillation does not necessarily cause permanent seal loss. (10.02(9); 10.08(2)(e).)
6. **Back pressure.** Positive pressure on the drainage side can push gas through the water seal or force water toward the fixture. Venting must control this pressure. (10.02(9); 10.08(2)(e).)
7. **Evaporation.** Water evaporates from an unused trap until the seal becomes too shallow or disappears. Floor/trough drains have specific resealing-device requirements and exceptions, described below. (10.02(9); 10.10(6)(e)2.)
8. **Capillary action.** Hair, lint, or other absorbent material extending from the seal over the weir can wick water toward the outlet and lower the seal. Removing the material addresses this cause; venting alone does not. (10.02(9); 10.08(2)(e).)

For the hydraulic explanations of siphonage, aspiration, momentum, and back pressure, see IAPMO's commentary on venting and trap-seal protection. The Massachusetts requirements are the CMR provisions cited above.

5.4 Floor and Trough Drains

Floor/trough drains must have an integral or separate trap with at least a 3-inch water seal and a removable strainer. The drain must be readily cleanable, its inlet easily accessible, and its outlet at least 2 inches in nominal diameter. (10.10(6)(a), (b), (d).)

All floor/trough drains generally require a readily accessible automatic trap-resealing device. The rule is not limited to infrequently used drains. The following exceptions are listed in 10.10(6)(e)2.:

1. Drains receiving continuous or semi-continuous discharge from indirect waste fixtures under 10.12 may qualify for the exception. (10.10(6)(e)2., Exception a.)
2. In a single room with multiple floor drains, product-accepted barrier-type trap-seal protection devices may serve up to 90% of the drains, provided at least one automatic trap-priming device is present. Barrier devices are not allowed under this exception in a room with only one floor drain. (10.10(6)(e)2., Exception b.)
3. An accessible wall hydrant within the room may replace a trap-priming device. (10.10(6)(e)2., Exception c.)

5.5 Cleanouts

Cleanouts provide access for clearing drainage piping. Their locations, sizes, and working clearances must allow the piping to be cleaned. (10.02(7); 10.08(3).)

1. **Spacing.** On horizontal drainage and branch drain piping 4 inches or smaller, cleanouts must be no more than 50 feet apart. On horizontal piping larger than 4 inches, the maximum spacing is 100 feet. (10.08(3)(a).)

2. **Changes of direction.** Provide an accessible cleanout at each change of direction of the building drain. For horizontal waste or soil lines and branch lines, provide one at each change greater than 45°. The building-drain rule is not limited to changes greater than 45°. (10.08(3)(d)1.–2.)
3. **Base of stacks.** Provide a cleanout at or near the base of each vertical storm-water conductor, waste stack, or soil stack. (10.08(3)(f).)
4. **Foundation wall.** The building drain needs a cleanout providing direct-line access through the building drain to the building sewer. Provide a pit or manhole if necessary. The piping arrangement must follow Example 7 and the applicable materials requirements. An additional full-size cleanout may be installed outside, no more than 5 feet beyond the foundation wall. (10.08(3)(g)1.–4.; 10.06, Table 1.)
5. **Inaccessible building drains.** For buildings with concrete slab floors, less than 36 inches of crawl space, or a cleanout that is not easily accessible, the building-drain cleanout may be outside, no more than 5 feet beyond the foundation wall. (10.08(3)(h).)
6. **Underground piping.** Extend underground drainage cleanouts vertically to or above finished grade, or to an accessible location immediately outside the building. (10.08(3)(c)1.–2.)
7. **Concealed piping.** Extend the cleanout through the finished wall or floor and terminate it flush, or provide a sufficiently large access panel to remove the plug and clean the piping. Cleanout plugs must not be permanently covered with cement, plaster, or other finishing material. A cover plate or access door must allow ready access. (10.08(3)(e); 10.08(3)(l)1.–2.)
8. **Direction.** Install the cleanout so it opens in the direction of drainage flow or at right angles to that flow. (10.08(3)(i).)
9. **Size.** For piping up to and including 4 inches, the cleanout must match the pipe's nominal size. For larger piping, the cleanout must be at least 4 inches. (10.08(3)(j).)
10. **Working clearance.** Cleanouts on pipes 3 inches or larger need at least 18 inches of clearance for clearing stoppages. Cleanouts smaller than 3 inches need 12 inches of clearance. (10.08(3)(k)1.–2.)
11. **Plugs.** Cleanout plugs must be brass or plastic and meet the latest testing standards. Heads must be raised or countersunk, square or hexagonal. Use a countersunk head where a tripping hazard may exist. Plastic plugs must match the material to which they connect. (10.08(3)(b)1.–5.)
12. **Equivalents.** The code lists a fixture trap with a union connection, a fixture with an integral trap, and a roof-drain cover removable without disturbing concealed rough piping as cleanout equivalents. (10.08(3)(m)1.–3.)
13. **Additional connections.** A cleanout opening must not be used to add plumbing unless another end-cleanout of equal access and capacity is provided. (10.08(3)(n).)
14. **Large exterior piping.** For the underground and dedicated-system piping covered by 10.08(3)(o)1., larger than 10 inches and outside a building, provide manholes at changes of diameter, alignment, grade, or elevation, and no more than 350 feet apart. The same clause provides a cleanout exception when the total developed drain length is less than 150 feet.⁴ Manholes must follow current standards and engineering practices. (10.08(3)(o)1.–2.)

⁴The December 2023 text prints the exception's spacing as "75 intervals" without a unit. The intended unit needs confirmation before applying that exception.

6 Water Pipe Sizing

CMR 10.14 uses three terms for its table-sizing method: *factor value*, *demand factor*, and *capacity value*. These play the load-estimating role often associated with water supply fixture units, but they are the values assigned by this particular method. Do not substitute drainage fixture units or another code's water supply fixture units for them. All code references below are to the December 8, 2023 version of 248 CMR 10.00.

6.1 The Sizing Method

CMR 10.14, Table 1 lists common fixtures, their minimum nominal fixture-branch sizes, and their factor values. For multiple fixtures on the same branch, add the factor values served by that branch. Next, multiply by the occupancy demand factor in Table 2 to obtain the capacity value:

$$F = \sum_i n_i f_i,$$

$$C = mF,$$

where n_i is the number of connections of a given type, f_i is its Table 1 factor value, and m is the Table 2 demand factor. With the capacity value in hand, use Table 3 to select the nominal pipe size. These are assigned sizing values; C is not a flow rate in gallons per minute. (10.14(2)(a)1.–5.)

Apply the calculation to each main, branch, and riser according to the connections it supplies. A branch serving

only part of the building does not carry the entire building's factor total. Keep hot and cold totals separately; a common incoming main supplying both carries their combined total, as illustrated in the code's example. (10.14(2)(a)1., 3., 8.)

The demand factor adjusts the connected factor total once. Do not apply it again when combining branches that already have capacity values. For branches with the same occupancy factor,

$$m(F_1 + F_2) = mF_1 + mF_2.$$

This identity does not establish an approved method for mixed occupancies. Table 2 supplies no general mixed-occupancy procedure and no factor for every possible process load. Unlisted or ambiguous cases need an established design basis; 10.14(2)(a)3. expressly permits a system designed by a Massachusetts professional engineer as an exception to the table method.

6.2 Minimum Fixture Branches

The individual fixture supply must meet the minimum nominal size in Table 1. A demand-factor calculation does not authorize reducing it below that minimum. For example, a commercial dishwasher has a factor value of 6 and a minimum 3/4-inch fixture supply, even if an occupancy adjustment gives a capacity value within the 1/2-inch range of Table 3. (10.14(2)(a)2., 5., Table 1.)

Fixture or device	Nominal inches	Factor
Bathtub, with or without single shower head	1/2	2
Bidet	3/8	1
Drinking water station	3/8	1
Dishwasher, domestic	1/2	2
Dishwasher, commercial	3/4	6
Kitchen sink, residential	1/2	2
Kitchen sink, commercial (pot and scullery)	3/4	6
Vegetable prep or bar sink, residential	1/2	2
Hand wash sink	3/8	1
Shampoo sink	3/8	1
Lavatory	3/8	1
Utility laundry sink, 1, 2, or 3 compartments	1/2	2
Shower valve, single head	1/2	2
Shower valve, multiple heads	3/4	6
Service or slop sink	1/2	2
Flushing-rim sink	3/4	6
Laundry valve	1/2	2
Urinal, flushometer type	3/4	6
Toilet, tank type	3/8	1
Toilet, flush valve type	1	12
Hose connection, sillcock, or wall hydrant	1/2	2

Table 1. Minimum sizes of individual fixture branches and factor values. Source: 248 CMR 10.14, Table 1; see 10.14(2)(a)2., 5.

Table 1 assigns a factor to a fixture type; the hot/cold calculation depends on the actual connections. The code's example assigns the full listed factor to each of the hot and cold sides of a dual-supplied fixture. Its domestic dishwasher is hot-only, and its tank toilets and wall hydrants are cold-only. This is the table method's accounting convention, not a statement that a mixed-water fixture physically consumes twice its discharge flow. (10.14(2)(a)8.)

6.3 Demand Factors and Capacity Values

Choose the demand factor for the applicable occupancy use. A factor of 0.50 means multiply the connected factor total by 0.50; it does not mean halve the pipe diameter. (10.14(2)(a)4., Table 2.)

Occupancy use	Demand factor
<i>Residential</i>	
One- or two-family dwelling	0.50
Multi-residential	0.35
Hotel	0.70
<i>School</i>	
General	0.75
Shower room	1.00
<i>Institutional</i>	
General	0.45
<i>Assembly</i>	
General	0.25
Restaurant, café	0.70
Club house	0.60
<i>Business and Mercantile</i>	
General	—
Industrial	0.25
Laundry	1.00
<i>INDUSTRIAL</i>	
General, exclusive of process piping	0.90

Table 2. Occupancy use demand factors. Source: 248 CMR 10.14, Table 2; see 10.14(2)(a)4.

Source ambiguity: The supplied code leaves the factor for Business and Mercantile—General blank, then prints “Industrial” with 0.25 and “Laundry” with 1.00 before a separate INDUSTRIAL heading. Those entries are retained as printed; the dash represents the blank cell, not zero. The table does not unambiguously assign 0.25 to Business and Mercantile—General. Obtain a Board interpretation for that case rather than silently filling the blank or choosing between the two industrial entries.

Nominal pipe or tubing size (inches)	Capacity value
1/2	1 to 4
3/4	4.1 to 9
1	9.1 to 16.5
1 1/4	16.6 to 28
1 1/2	28.1 to 55
2	55.1 to 107.5
2 1/2	107.6 to 182.5
3	182.6 to 287.5
3 1/2	287.6 to 425
4	425.1 to 700
5	700.1 to 1100
6	1100.1 to 1300

Table 3. Capacity values for services, mains, risers, and branches. Source: 248 CMR 10.14, Table 3; see 10.14(2)(a)3.–4.

The listed ranges contain small numerical gaps. For example, $9 \times 0.45 = 4.05$, between 4 and 4.1. The code does not state a rounding rule here. A conservative selection is the next larger listed size, 3/4 inch, because 1/2 inch is listed only through 4. Do not round a load downward to make it fit a smaller pipe. This gap-handling convention is

an interpretation, not an additional quoted code rule.

Table 3 lists no service or distribution size below 1/2 inch and no capacity above 1300. Do not extrapolate it to invent an unlisted size or capacity. Certain individual fixtures have 3/8-inch minimum supplies under Table 1; this is not a missing Table 3 row. (10.14(2)(a)2.–5.)

The printed references to “10.14(4): Tables 1, 2, and 3” in this edition are outdated internal cross-references. The sizing provisions and these tables appear under 10.14(2)(a); 10.14(4) addresses disinfection.

6.4 One-Family Example

The following is the fixture list and hot/cold factor accounting in the code’s example. A dash means no connection on that side. The numbers are factor totals, not GPM. (10.14(2)(a)8.)

Fixtures	Hot	Cold
Two tank-type toilets	—	2
Two lavatories	2	2
One bathtub	2	2
One shower stall	2	2
One utility sink or laundry valve	2	2
One domestic dishwasher	2	—
One kitchen sink	2	2
Two wall hydrants	—	4
Total factor value	12	16

Table 4. Hot and cold factor totals in the example at 248 CMR 10.14(2)(a)8.

For the common incoming main, combine both totals:

$$F_{\text{main}} = 12 + 16 = 28,$$

$$C_{\text{main}} = 28(0.50) = 14.$$

Since 14 lies between 9.1 and 16.5, Table 3 gives a **1-inch main**. This is the result given in the code. (10.14(2)(a)8.a.–c.)

Extending the same method to separate distribution branches, suppose one branch supplies all the listed hot-water connections and another supplies all the listed cold-water connections after the water-heater feed has separated:

$$C_{\text{hot}} = 12(0.50) = 6,$$

$$C_{\text{cold}} = 16(0.50) = 8.$$

Both are within the 3/4-inch range. The cold feed to the water heater carries the hot-side demand; do not count the heater again as an additional fixture on top of those hot-water connections. Check the heater’s connection and operating requirements as well. The 1-inch main and these

3/4-inch branches are table selections; satisfactory pressure still has to be established. (10.14(2)(a)1.–5., (c)–(d).)

For a smaller branch serving only the hot connections of the bathtub and one lavatory,

$$C = (2 + 1)(0.50) = 1.5,$$

so Table 3 gives 1/2 inch. The individual bathtub and lavatory supplies must still meet their respective Table 1 minimums of 1/2 and 3/8 inch.

6.5 Pressure at the Fixtures

Tables 1–3 do not account explicitly for developed length, elevation, or equipment pressure loss. A table-sized pipe must also deliver the required flow pressure at the fixture. Flow pressure is pressure while water is being supplied; a satisfactory static reading alone does not establish that the piping can deliver the required flow. (10.14(1)(c), (2)(c)–(d).)

Fixture or device	Flow pressure (PSI)
Lavatory faucet, residential	8
Lavatory faucet, non-residential	8
Kitchen or bar faucet, residential	8
Sink faucet, non-residential	8
Bathtub faucet	8
Laundry valve or faucet, residential	8
Shower head	8
Tank-type toilet	8
Flushometer-type toilet	15–20
Flushometer-type urinal	15
Drinking water station	Not stated
Outside faucet or hydrant	10

Table 5. Pressure entries from 248 CMR 10.14, Table 4; see 10.14(2)(c). The flow-rate column is not reproduced here.

For a flushometer toilet, Table 4 prints a 15–20 PSI range; use the requirement applicable to the selected equipment rather than assuming every valve operates adequately at 15 PSI. The drinking-water-station pressure cell is blank: the adjacent 0.75 is in the flow-rate column, not a pressure requirement. Use the equipment's required operating pressure where the table provides no number.

Do not treat flush volume as an instantaneous flow rate. A toilet's gallons per flush measures water per event; GPM measures water per unit time. Table 4 places toilet and urinal consumption figures under a GPM heading, so that column cannot be used as a list of instantaneous fixture demands. The separate toilet and urinal provisions explicitly express consumption per flush. (10.10(2)(f), (3)(c); 10.14(2)(c), Table 4.)

On-demand domestic water heaters are an express exception in 10.14(2)(c). The Board's *On Demand Water Heaters* interpretation retains pipe-sizing, adequate incoming-pressure, and manufacturer installation and sizing requirements. Account for the selected heater's pressure loss, operating-flow limits, and output at the required temperature rise.

Low and High Pressure

When the source cannot provide the required fixture flow pressures, the code requires a booster pump and pressure tank or another compliant means. A properly sized booster pump is required for one-, two-, and three-family dwellings when the supply cannot meet probable peak demand; booster systems for other buildings must be designed by a Massachusetts professional engineer. (10.14(2)(d), (d)1.a.–b.)

If pressure at a fixture, device, or appurtenance exceeds 80 PSIG, a pressure-reducing valve is required upstream to limit the pressure to 80 PSIG. A gauge with a minimum range of 0–150 PSIG must be within 24 inches downstream of that valve. The provision excepts water-service supply piping upstream and downstream of a water-pressure booster. (10.14(2)(e).)

6.6 Flow, Diameter, and Pressure Loss

The following equations describe the hydraulics; they are not substitutes for the code's table method or its professional-engineer exception. Use an independently established design flow for each pipe section, accounting for the actual equipment and simultaneous demands. CMR Table 3 supplies no capacity-value-to-GPM conversion.

Actual Inside Diameter

For a full circular pipe, volume flow is cross-sectional area times average velocity:

$$Q = Av.$$

With actual inside diameter d_i in inches, average velocity v in feet per second, and Q in US gallons per minute,

$$\begin{aligned} Q &= \frac{\pi d_i^2}{4(144)} v \frac{1728}{231} \quad (60) \\ &\approx 2.44799 d_i^2 v, \\ v &\approx \frac{0.408498 Q}{d_i^2}. \end{aligned}$$

The constants only convert units. For example, 10 GPM through an actual 1.000-inch bore gives about 4.085 feet per second. This does not say that every nominal 1-inch pipe has that bore or that this velocity is suitable for every material and application.

Nominal size is a designation. Actual bore depends on pipe material, type, and wall thickness; inserts and fittings may restrict it further. Use the selected product's dimensions and hydraulic data.

The Copper Development Association recommends limiting copper-tube velocities to 8 feet per second for cold water and 5 feet per second for hot water up to about 140°F, with lower limits for hotter water and consideration of lower limits in small tubing. These are copper design recommendations, not a universal velocity limit stated in CMR Table 3. See the *Copper Tube Handbook*, "Pressure System Sizing" and "Water Velocity Limitations."

Pressure Budget

For an approximate pressure budget, neglecting changes in velocity head, let:

- P_s be the available source pressure under design-flow conditions, in PSI;
- P_r be the required residual pressure at the fixture, in PSI;
- Δz be the fixture's elevation above the source, in feet;
- ΔP_e be the combined meter, backflow-device, heater, treatment-equipment, and other separately calculated equipment losses, in PSI.

The pressure available for pipe and fitting friction is approximately

$$\Delta P_{\text{available}} = P_s - P_r - 0.433 \Delta z - \Delta P_e.$$

The 0.433 PSI per foot uses the approximate weight density of ordinary water. Elevation gain consumes pressure; elevation loss makes Δz negative. Evaluate each equipment loss at the flow through that equipment, and do not subtract a loss twice if it is already reflected in the source-pressure measurement.

For example, take 60 PSI available while flowing, a fixture 20 feet higher, 10 PSI in equipment losses, and an 8 PSI fixture requirement:

$$\begin{aligned}\Delta P_{\text{available}} &= 60 - 8 - 0.433(20) - 10 \\ &= 33.34 \text{ PSI.}\end{aligned}$$

This leaves 33.34 PSI for pipe and fitting losses along that path. It is a pressure-budget example, not a GPM estimate or a final pipe-size selection. If the available amount is zero or negative, there is no positive allowance left for friction.

Use pressure-loss data for the actual material and bore. Check whether a chart states loss per foot or per 100 feet. Add fittings by an appropriate equivalent-length or loss-coefficient method, but do not count the same fitting both ways. Different sections of a path may carry different flows, so calculate their losses separately and add them. The most demanding path need not be the longest one. The *Copper Tube Handbook*, Tables 14.6–14.7 provides copper-tube friction data and fitting allowances.

Darcy–Weisbach Equation

For a straight pipe section, the friction head loss is

$$h_f = f_D \frac{L}{D} \frac{v^2}{2g},$$

where h_f , L , and actual inside diameter D are in feet, v is in feet per second, $g \approx 32.174$ feet per second squared, and f_D is the dimensionless *Darcy* friction factor. It depends on Reynolds number and relative roughness; it is not a universal constant for all water piping. For ordinary water,

$$\Delta P_f \approx 0.433 h_f \text{ PSI.}$$

The equation shows why diameter alone cannot establish GPM: length, available pressure, fluid properties, and friction also matter. If f_D is treated as constant for a comparison, fixed friction loss and fixed length give $Q \propto D^{5/2}$, rather than the $Q \propto D^2$ relation obtained at fixed velocity. Neither assumption creates a conversion from the code's capacity values to flow.

6.7 Capacity Value vs. Diameter

The exact relationship between nominal diameter and the capacity value is a bit elusive when looking at numbers alone. Since cross-sectional area grows as the square of the diameter, one could try a model $y = Ax^2$, where x

is nominal diameter in inches and y is the midpoint of the corresponding Table 3 capacity interval. Trying a few values gives:

$$\begin{aligned}A &= \frac{(16.5 + 9.1)/2}{1^2} = 12.8, \\ A &= \frac{(107.5 + 55.1)/2}{2^2} \approx 20.33, \\ A &= \frac{(287.5 + 182.6)/2}{3^2} \approx 26.12, \\ A &= \frac{(700 + 425.1)/2}{4^2} \approx 35.16.\end{aligned}$$

These values are not constant. A single quadratic model does not reproduce the midpoint data.

Going instead for a power-law model, write

$$y = Ax^B,$$

$$\ln y = \ln A + B \ln x.$$

Ordinary least-squares regression in logarithms, using all 12 Table 3 interval midpoints, gives

$$\hat{y} \approx 13.8583 x^{2.56857}. \quad (1)$$

The hat marks a fitted value. This is an approximation to the *midpoints*, not a formula for the upper capacity limits and not an authorized replacement for Table 3.

Diameter vs. Capacity Value

Solving the fitted equation for x gives

$$\begin{aligned}x &\approx \left(\frac{\hat{y}}{13.8583} \right)^{1/2.56857} \\ &\approx 0.35934 \hat{y}^{0.389322}.\end{aligned}$$

This inversion is algebraically valid, but it does not turn the fit into a sizing rule. For example, substituting a capacity value of 9 gives approximately 0.845 inch. Rounding that up to the next listed nominal size gives 1 inch, whereas Table 3 places 9 within the 3/4-inch range. Use the table's ranges directly for code sizing.

Capacity Value vs. Volume Flow

The WC&P article, “Hydrodynamic Design, Part 2” (February 3, 2013) used in the original notes describes its flow chart at 15 PSI loss *per 100 feet*; its diameter column is explicitly *inside diameter*. It is therefore not a general chart of GPM for nominal sizes at any length.

A logarithmic fit of its ten listed diameter/flow pairs does reproduce the original numerical result,

$$\hat{Q} \approx 19.4946 d_i^{2.69626}.$$

However, this flow fit and Equation (1) do not even use the same diameter definition. The first uses actual bore, while the second uses nominal size.

Even if one formally divides the original rounded fits using the same numerical diameter x , the result is

$$R \approx \frac{13.858}{19.495} x^{-0.1277} \approx 0.71085 x^{-0.1277}.$$

The exponent is not zero. From $x = 0.5$ to $x = 4$, this expression falls from about 0.777 to 0.596, a decrease of about 23%. More fundamentally, comparing two fitted curves does not establish a physical or code-defined relationship between their outputs.

Consequently, neither $C \approx 0.71085Q$ nor $Q \approx 1.4068C$ is a justified sizing conversion. Keep the code's capacity calculation and the hydraulic flow/pressure calculation separate, and satisfy both the table requirements and the system's operating requirements.

6.8 Other Requirements Affecting the Design

- **Hot-water circulation.** Where developed hot-water length from the source to the farthest fixture supply exceeds 75 feet, total return circulation is required. For this provision, the source is the water heater or recirculation loop. The minimum recirculating line is 1/2 inch; this minimum alone does not establish its required circulation flow or pump size. (10.14(2)(f).)
- **Water hammer.** Systems with quick-acting or solenoid valves require pressure-absorbing devices.

Locate them as close as possible to those valves and make them accessible. Air chambers must have a means of restoring their air charge; product-accepted mechanical devices must follow the manufacturer's installation specifications. (10.14(2)(b)1.a.–c., 3.)

- **Full-port valves.** The main control valve must be full-port and at least the size of the building water-service pipe. Main and branch/riser controls and other devices on mains and branches are subject to the full-port requirement. Include the actual components in the hydraulic check. (10.14(3)(b)1.–2., (e).)
- **Thermal expansion.** When a metering device with a check valve or backflow preventer creates a closed system, install a properly sized thermal-expansion tank as close as possible to that metering device. A larger supply pipe does not replace this requirement. (10.14(3)(j).)
- **Multipurpose fire sprinklers.** A potable-water system incorporating residential fire sprinklers has additional design demands. For the one- and two-family NFPA 13D systems described by the code, follow a Massachusetts professional engineer's design complying with CMR and the specified 2022 edition of NFPA 13D. (10.14(1)(a).)

7 Waste Pipe Sizing

Waste pipe sizing makes use of the term *fixture unit* to quantify the drainage load assigned to a fixture. In this section, DFU means drainage fixture unit. The assigned values and sizing limits come from 248 CMR 10.15. All code references below are to the December 8, 2023 version of 248 CMR 10.00.

7.1 Fixture Units

For each pipe section, add the fixture units of the fixtures discharging through it and size the pipe for that load. Table 6

reproduces the values in 10.15, Table 1. (10.15(2)(a), (3).)

The definition of *Fixture Unit* in 10.03 refers to one cubic foot of water drained through a $1\frac{1}{4}$ -inch pipe in one minute. That definition does not mean a connected load of F DFU produces a steady flow of $7.5F$ gallons per minute. Use the code's assigned fixture values and capacity tables for sizing.

Continuous or semi-continuous sewage-waste discharges are generally counted at 2 DFU per gallon per minute. For example, a 12 GPM discharge represents 24 DFU under this rule. There is a separate exception for ejector pumps installed under 10.15(9), Table 5, with a maximum discharge of 20 GPM. (10.15(2)(b).)

Fixture or group of fixtures	DFU
Bathtub or tub and shower unit	2
Bidet	2
Dental chair unit or cuspidor	1
Dental lavatory	1
Drinking fountain/water station	1
Dishwasher, commercial	6
Dishwasher, residential	1
Floor/trench drain, 2-inch	4
Floor/trench drain, 3-inch	5
Floor/trench drain, 4-inch	6
Kitchen sink, residential, with or without disposer	2
Lavatory with $1\frac{1}{4}$ -inch outlet	1
Laundry connection, residential	3
Laundry/utility sink	2
Shower stall, residential	2
Showers, group, per head	2
Surgeon's sink	3
Flushing-rim sink, with valve	6
Service sink with trap standard	3
Service sink with P-trap	2
Commercial pot, scullery, or similar sink, each section	4
Shampoo sink	2
Toilet, tank type	4
Toilet, valve operated	6
Urinal, pedestal, siphon jet blowout	6
Urinal, wall lip	4
Urinal, waterless	1
Wash sink, circular or multiple, each 20 inches of usable length	1
<i>Sizes for fixtures not listed above</i>	
$1\frac{1}{4}$ inches or less	1
$1\frac{1}{2}$ inches	2
2 inches	3
$2\frac{1}{2}$ inches	4
3 inches	5
4 inches	6

Table 6. Fixture unit values. Source: 248 CMR 10.15, Table 1; see 10.15(2)(a)–(b).

Table 1 has additional notes concerning grease interceptors, continuous flows, and floor-drain sizing. In this edition, two of the printed cross-references are outdated: the relevant grease-interceptor branch-sizing provision is

10.09(1)(b)2.d.; the floor/trough drain sizing provision is 10.10(6)(d). The continuous-flow rule is 10.15(2)(b).

Fixture-unit values do not override minimum pipe and trap sizes. A lavatory's listed outlet size, for example, is

not permission to reduce its trap below the minimum in 10.08(2)(b), Table 1.

7.2 Pitch and Pipe Classification

CMR 10.15, Table 2 lists building-drain capacities at three pitches. These are table columns, not an exhaustive list of permitted pipe slopes. If s is the fall in inches per horizontal foot, the downward angle from horizontal is

$$\theta = \arctan\left(\frac{s}{12}\right).$$

The corresponding angles are:

- 1/8 inch per foot: 0.5968°.
- 1/4 inch per foot: 1.1935°.
- 1/2 inch per foot: 2.3859°.

The code classifies a pipe as vertical when it is 45° or less from vertical, and horizontal when it is more than 45° from vertical. Thus, measured from horizontal, 45° belongs to the vertical classification. (10.03, definitions of *Horizontal Pipe* and *Vertical Pipe*.)

Horizontal drainage piping must have a consistent uniform pitch. For diameters of 3 inches or smaller, the general minimum is 1/4 inch per foot; for larger diameters, it is 1/8 inch per foot. An engineered departure is allowed where the computed discharge velocity is at least 2 feet per second and the system is designed by a Massachusetts professional engineer. Building-drain sizing must also follow Table 2. (10.05(2)(a)–(e).)

7.3 Horizontal Waste Pipes

CMR 10.15 distinguishes between horizontal branch drains and building drains. A branch collects part of the system's load. The building drain is the lowest drainage piping collecting discharge and conveying it toward the building sewer; the code's definition includes its specified extension beyond the foundation wall. (10.03, definitions of *Branch* and *Building Drain*.)

Table 7 has one capacity column for horizontal branches and three pitch-dependent columns for building drains. Do not use a building-drain column to increase a branch's allowable load. A dash supplies no tabulated capacity for that combination. (10.15(3), Table 2.)

Diameter (inches)	Horizontal branch (DFU)	Building drain (DFU)		
		1/8 in./ft.	1/4 in./ft.	1/2 in./ft.
1½	3	—	—	—
2	6	—	—	—
2½	12	—	—	—
3	34*	—	40*	48*
4	160	180	216	250
5	360	390	480	575
6	620	700	840	1,000
8	1,400	1,600	1,920	2,300
10	2,500	2,900	3,500	4,200
12	3,900	4,600	5,600	6,700
15	7,000	8,300	10,000	12,000

*Not more than four water closets.

Table 7. Maximum loads for horizontal drains. Source: 248 CMR 10.15, Table 2.

For example, a 200 DFU load exceeds the 180 DFU capacity of a 4-inch building drain at 1/8 inch per foot, but is within its 216 DFU capacity at 1/4 inch per foot. A horizontal branch carrying the same load needs at least 5 inches by the branch column, since the 4-inch branch limit is 160 DFU. These are capacity checks; the installation must also meet the other code requirements. (10.15, Table 2.)

Minimum Sizes and Special Conditions

- A soil or waste stack cannot be smaller than its largest connected horizontal waste branch. (10.15(4).)
- Include provisions for future fixtures when determining drain and vent sizes. (10.15(5).)
- Underground drainage is generally at least 2 inches. Sanitary piping through an exterior foundation wall is generally at least 4 inches, subject to the specific exceptions in that provision. A 3-inch capacity shown in Table 2 does not cancel this foundation-wall requirement. (10.15(6)(a), (b)1., Exceptions a.–e.)
- A residential kitchen sink must not discharge into a horizontal drain smaller than 3 inches if that drain receives discharge from a flat-bottom fixture. This can govern even when the DFU total alone would permit a smaller pipe. (10.15(8)(c)2.)

7.4 Stacks with One or Two Branch Intervals

The story is different for vertical pipes. A *branch interval* generally corresponds to a story height, but must be at least 8 feet in vertical height and is the portion of the stack receiving the horizontal branches from a floor or story.

Count branch intervals, not simply the number of branch connections. (10.03, definition of *Branch Interval*.)

Table 8 gives the maximum load on a stack with one or two branch intervals. CMR supplies the limits without a derivation. Their origin cannot be established just by fitting the numbers. (10.15, Table 3.)

Stack diameter (inches)	Maximum stack load (DFU)
$1\frac{1}{2}$	4
2	8
$2\frac{1}{2}$	20
3*	48
4	240
5	540
6	930
8	2,100
10	3,750
12	5,850
15	10,500

*Not more than four water closets.

Table 8. Maximum loads for soil and waste stacks with one or two branch intervals. Source: 248 CMR 10.15, Table 3.

Power-Law Analysis

Let $x = d/(1 \text{ inch})$ be the numerical nominal diameter, and let y be the numerical maximum load in DFU. Proposing

$$y = Ax^B$$

and fitting $\log y = \log A + B \log x$ by least squares gives the following piecewise approximation to Table 3:

$$\hat{y} = \begin{cases} 0.81698x^{3.5783}, & 1.5 \leq x \leq 3, \\ 5.5947x^{2.8106}, & 4 \leq x \leq 15. \end{cases}$$

The first fit uses the four listed diameters through 3 inches; the second uses the seven listed diameters from 4 through

15 inches. These are descriptions of the data, not sizing formulas. For example, the first fit predicts about 9.76 DFU for a 2-inch stack, where the code permits only 8. Use Table 3 for sizing.

7.5 Stacks with Three or More Branch Intervals

Table 9 gives two different limits: the load entering within any one branch interval and the total load on the stack. Both must be satisfied. All branches entering within the same interval contribute to that interval's load. (10.15, Table 4.)

Diameter (inches)	Number of branch intervals														Maximum total DFU
	3	4	5	6	7	8	9	10	11	12	13	14	15		
2	3	—	—	—	—	—	—	—	—	—	—	—	—	10	
2½	8	7	—	—	—	—	—	—	—	—	—	—	—	28	
3*	20	18	17	16	15	14	13	12	11	10	10	10	10	102	
4	100	90	84	80	77	75	73	72	71	70	69	68	68	530	
5	225	205	190	180	175	170	165	162	159	157	156	154	153	1,400	
6	385	350	325	310	300	290	285	280	275	271	268	266	263	2,900	
8	875	785	735	700	675	655	640	630	620	612	606	600	594	7,600	
10	1,560	1,405	1,310	1,250	1,205	1,170	1,140	1,125	1,110	1,095	1,180†	1,075	1,062	15,000	
12	2,435	2,195	2,045	1,950	1,875	1,825	1,790	1,755	1,730	1,705	1,685	1,670	1,655	26,000	
15	4,375	3,935	3,675	3,500	3,380	3,280	3,210	3,150	3,110	3,060	3,030	3,000	2,975	50,000	

Entries under interval counts are maximum DFU within any one interval. Dashes mean no value is supplied.

*Not more than three water closets. For 3-inch stacks with more than 15 branch intervals, no single interval may exceed 10 DFU.

†The supplied code prints 1,180 for the 10-inch, 13-interval entry. It breaks the row's trend and does not agree with the formula discussed below. This apparent error needs clarification before that cell is used for sizing; it has not been silently corrected here.

Table 9. Limits per branch interval and for the entire stack. Source: 248 CMR 10.15, Table 4 and its notes.

Per-Interval Formula

For stacks exceeding 15 branch intervals, the formula printed below Table 4 is

$$L = \frac{N}{2n} + \frac{N}{4} = N \left(\frac{1}{2n} + \frac{1}{4} \right),$$

where N is the maximum stack load from Table 3, n is the number of branch intervals, and L is the permissible load within any one interval. The special 10 DFU limit for a 3-inch stack with more than 15 intervals still applies. (10.15, Table 4, formula and footnote.)

The formula also explains many of the table entries for larger diameters, but it does not reproduce every cell exactly. Use the published values for 3–15 intervals rather than replacing them with computed values. The code itself illustrates the formula with a 4-inch, 10-interval example:

$$L = 240 \left(\frac{1}{2 \times 10} + \frac{1}{4} \right) = 72 \text{ DFU.}$$

This agrees with the corresponding Table 4 cell. For an example within the formula's stated range, a 4-inch stack with 20 intervals gives

$$L = 240 \left(\frac{1}{40} + \frac{1}{4} \right) = 66 \text{ DFU per interval.}$$

The total stack load must also remain within the stack's total-load limit. (10.15, Table 4.)

For large n ,

$$L \rightarrow \frac{N}{4}.$$

This is the limiting value of the formula for a single branch interval. It is not permission to load every interval to $N/4$, and it does not override the specific 3-inch-stack note.

Total Stack Load

Suppose a 4-inch stack has 15 branch intervals. Table 4 permits up to 68 DFU in any one interval, with a maximum of 530 DFU on the entire stack. Loading every interval to 68 would give

$$15 \times 68 = 1,020 > 530.$$

That arrangement fails the total-load check. There is no discrepancy: a local loading limit and a total loading limit control different conditions. (10.15, Table 4.)

For equal loads in all 15 intervals, the total limit restricts the average to

$$\frac{530}{15} = 35\frac{1}{3} \text{ DFU per interval.}$$

For a 10-inch stack, $15 \times 1,062 = 15,930$, which also exceeds its total limit of 15,000 DFU. How close the product comes to the final column does not remove either check.

If F_i is the connected load entering at interval i , L the interval limit, and T the total limit, the two checks are

$$F_i \leq L \quad \text{for every } i, \quad \sum_{i=1}^n F_i \leq T.$$

Each horizontal branch must also meet its own Table 2 limit.

A logarithmic least-squares fit of the total-load column for the listed diameters 4 through 15 inches gives

$$\hat{y} = 5.7853x^{3.3935}.$$

Again, this is only a mathematical description. It predicts about 639 DFU at 4 inches, exceeding the code limit of 530 by about 20.5%. It cannot replace Table 4.

Stack Offsets

An offset at 45° or less from vertical may be sized as a straight vertical stack, with the stated relief-vent requirement when a branch connects within 2 feet above or below it. Offsets greater than 45° from vertical require the horizontal-drain sizing procedure and the separate checks for the stack above and below the offset. (10.15(7)(a), (b)1.–4.)

Offsets above the highest branch affect stack-vent developed length. Offsets below the lowest branch have their own sizing provision. The short-stack or multistory table alone does not settle an offset installation. (10.15(7)(c), (d).)

8 Venting

Venting provides air movement through the drainage system and protects trap seals from siphonage and back pressure. The principal requirements are in 248 CMR 10.16. Code references below use the December 8, 2023 edition (10.03, Vent System; 10.02.9).

8.1 General Knowledge

1. **Trap-seal protection.** Design drainage and venting for adequate air circulation and protection against siphonage, leakage, aspiration, momentum, oscillation, back pressure, evaporation, and capillary action during ordinary use (10.02.9).
2. **Pressure limit.** A fixture trap shall not be subjected to a pressure differential greater than one inch of water. Protect its seal using the permitted venting arrangements in 10.16. The usual liquid-seal depth is two to four inches, with deeper seals permitted for special conditions (10.08.2.e).
3. **Vent stack.** A vertical vent pipe providing air circulation to and from the drainage system (10.03, Vent Stack).
4. **Stack vent.** The portion of a soil or waste stack six inches above the flood-level rim of its highest connected fixture, terminating under 10.16. Stack venting is the method of venting fixtures through a soil or waste stack (10.03, Stack Vent; Stack Venting).
5. **Individual and branch vents.** An individual vent serves a fixture drain and joins the vent system above the fixture or terminates above the roof. A branch vent joins one or more individual vents to a vent stack or stack vent (10.03, Individual Vent; Branch Vent).
6. **Common and continuous vents.** A common vent is a vertical vent serving two fixtures. A continuous vent continues upward from the vertical drain it serves (10.03, Common Vent; Continuous Vent).
7. **Wet vent.** A waste pipe that also serves as a vent on the same floor level (10.03, Wet Vent).
8. **Relief and yoke vents.** A relief vent provides additional air circulation between drainage and vent systems. A yoke vent connects upward at 45° from a soil or waste stack to a vent stack to prevent stack pressure changes (10.03, Relief Vent; Yoke Vent).

8.2 The 5-6-8-10 Rule

The maximum developed length of the fixture drain from the trap weir to the vent fitting depends on the pipe diameter. This is measured along the pipe, including changes of direction; it is not simply the straight-line distance between the fixture and vent. (10.16(10)(a); 10.03, definition of *Developed Length*.)

Diameter (inches)	Maximum length (feet)
1½	5*
2	6
3	8
4	10
Slope not to exceed 1/4 inch per foot.	

Source: 10.16(10), Table 1. The general minimum-pitch requirements also apply. (10.05(2)(b), (c).)

*The supplied 2023 table prints the first length as 5". Five *feet* is the reading used here, consistent with the earlier official Massachusetts table, which explicitly labels the distance column in feet. This corrects an apparent unit misprint; it is not a change to the other three entries. The 2023 sentence in 10.16(10)(a) also refers to subsection (12), although the table appears under (10).

The vent opening generally cannot be below the trap weir, with the stated exclusions for toilets and similar fixtures and the specific flat-bottom-fixture exception. Those exceptions must be read in full before applying them. (10.16(10)(b)1.–2.)

Geometry of a Sloped Trap Arm

To examine the geometry, consider a straight circular pipe falling toward the vent by an angle θ . Let L be its developed length, D its actual inside diameter measured perpendicular to the pipe axis, and Δz the vertical distance from the trap-weir plane to the upper inside edge at the downstream cross-section. This idealization places the upstream invert at the trap-weir elevation and ignores fittings.

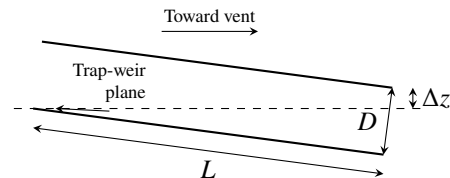


Figure 6. Straight sloped pipe; angle and diameter exaggerated for clarity.

The downstream invert falls by $L \sin \theta$, while the diameter has a vertical component $D \cos \theta$. Therefore,

$$\Delta z = D \cos \theta - L \sin \theta.$$

The simpler expression $D - L \sin \theta$ neglects the inclination of the diameter. The difference is small at plumbing slopes, but the distinction matters when defining an exact model.

Measured within the cross-section perpendicular to the pipe, the segment height above the trap-weir plane is

$$h = \frac{\Delta z}{\cos \theta} = D - L \tan \theta.$$

With ℓ denoting the numerical length in feet, d the numerical diameter in inches, and s the numerical fall in inches per horizontal foot,

$$L = 12\ell \text{ inches}, \quad \tan \theta = \frac{s}{12}, \quad \frac{h}{D} = 1 - \frac{\ell s}{d}.$$

Assumed D (inches)	L (feet)	Pitch (in./ft.)	Δz (inches)	h/D (%)	Segment area ratio (%)
1.5	5	1/4	0.24995	16.67	10.96
2	6	1/4	0.49989	25.00	19.55
3	8	1/4	0.99978	33.33	29.18
4	10	1/8	2.74985	68.75	73.30
4	10	1/4	1.49967	37.50	34.25

Table 10. Geometric comparison at a horizontal reference plane. These are not required air-space percentages or predicted operating water levels.

As a ratio to pipe diameter, h/D is a ratio of lengths, not areas. For a circular segment of height h , define $q = h/D$. The fraction of the circle above the reference plane is

$$R(q) = \frac{1}{\pi} \left[\arccos(1 - 2q) - 2(1 - 2q)\sqrt{q(1 - q)} \right], \quad 0 \leq q \leq 1.$$

The inverse cosine is in radians. Applying this formula gives the final column of Table 10.

The first three segment-height ratios are 1/6, 1/4, and 1/3. The 4-inch case changes because the chosen minimum pitch drops to 1/8 inch per foot. At 1/4 inch per foot, the same 4-inch, 10-foot model gives an area ratio of about 34%, rather than 73%.

These percentages describe only the chosen geometry. They do not establish that a $1\frac{1}{2}$ -inch pipe needs 11% of its area open for venting, or that a 4-inch pipe must reserve three quarters of its area for air. Actual flow depth, air movement, discharge rate, fittings, and pressure changes are not determined by this model. Use the code's trap-arm length, pitch, vent-location, and seal-protection requirements for installation. (10.16(10)(a)–(b), Table 1; 10.05(2); 10.08(2)(e).)

8.3 Fixture Vent Location

1. **Crown venting.** No vent shall be installed within two pipe diameters of the trap weir (10.16.1.b).
2. **Above the weir.** Except for toilets and similar fixtures, the vent opening from a soil or waste pipe shall not be below the trap's top weir, subject to the following exception (10.16.1.d, 10.16.10.b.1–2).

These identities apply to the straight-pipe model. They do not derive the code's allowed lengths or describe the actual water surface during discharge.

For comparison with the old calculations, assume the inside diameter equals the nominal size and use each size's general minimum pitch. The results are shown in Table 10. Actual inside diameter depends on the piping material and dimensions.

3. **Flat-bottom exception.** A below-weir vent is permitted only when the fixture has a flat bottom of at least 144 square inches; its horizontal waste meets Table 1; its vertical waste is at least one pipe size larger than the trap and waste arm; and the vent opening is as high and as close to the fixture as possible (10.16.10.b.2.a–c).
4. **Floor-outlet drop.** For a floor-outlet toilet or similar fixture, the distance from finished floor to the horizontal drain's centerline shall not exceed 20 inches without individual venting (10.16.10.c.1–2).
5. **Horizontal continuation.** A horizontal soil or waste pipe's continuation shall not serve as a vent except as permitted by 10.16.5 and when a fixture waste of no more than two fixture units connects to the vertical extension of that horizontal piping (10.16.1.c, Exceptions.1–2).
6. **Air-admittance valves.** Automatic vent fittings and air-admittance valves require special permission from the Board (10.16.1.e).

8.4 Vent Grades and Connections

1. **Drain back.** Uniformly grade vents under 10.05.2 and connect them so they drain by gravity to a soil or waste pipe. The general minimum pitch is 1/4 inch per foot for pipe three inches or smaller and 1/8 inch per foot for larger pipe (10.16.4.a, 10.05.2.b–c).
2. **Takeoff above centerline.** A vent connecting to a horizontal soil or waste pipe shall be taken off above the drain's centerline (10.16.4.b.1.a).

3. **Rise before offset.** For fixtures other than floor-mounted fixtures, rise vertically or at 45° from vertical to at least six inches above the fixture's flood-level rim before offsetting horizontally (10.16.4.b.1.b).
4. **Floor-mounted exception.** A vent may extend horizontally above the drain's centerline to the nearest practical point for a vertical rise. It shall initially leave the drain above centerline at least 45° from horizontal before running horizontally (10.16.4.b.1.c).
5. **Connection height.** Connect a vent pipe to a vent stack or stack vent at least six inches above the highest served fixture's flood-level rim (10.16.4.c.1).
6. **Horizontal vent height.** Horizontal branch, relief, and loop vents shall be at least six inches above the highest served fixture's flood-level rim (10.16.4.c.2).

8.5 Vent Stacks and Stack Vents

1. **Main vent requirement.** All building drains within a structure shall have at least one full-size main stack vent or a vent stack no smaller than three inches. Determine the appropriate size using 10.16.Table.2 (10.16.2.a).
2. **Three or more branch intervals.** Provide at least one main vent stack sized by Table 2 from the building drain to the open air above the roof, or reconnect it to a main stack vent six inches above the highest served fixture's flood-level rim (10.16.2.a).
3. **Required companion vent.** Install a vent stack or main vent with a soil or waste stack wherever individual, relief, or other branch vents are required (10.16.2.b).
4. **Base connection.** Main vents and vent stacks shall connect full size at their bases to the building drainage or main soil or waste pipe at or below the lowest fixture branch (10.16.2.c.1).
5. **Top connection.** Extend vents undiminished above the roof, or reconnect them to the main soil or waste stack at least six inches above the flood-level rim of the highest fixture discharging into it (10.16.2.c.2).
6. **Vent headers.** Join vent stacks and stack vents to the header at their tops; connect the header to a roof extension. More than two four-inch soil or waste stacks require a five-inch roof extension; more than four require six inches (10.16.2.e.1–4).

8.6 Wet Venting

1. **Bathroom arrangement.** In a bathroom with a two-inch horizontal waste, a two-inch extension of the horizontal drain connecting to a lavatory may serve as a wet vent for the fixtures served. This also applies to double or back-to-back bathrooms (10.16.5.a).
2. **Centerline.** The lowest portion of the wet-vent pipe shall break the centerline of the horizontal drain it serves (10.16.5.a; 10.16.Example.11).
3. **Excluded fixtures.** Waste and vent piping serving a kitchen sink, garbage disposal, dishwasher, washing machine, or any culinary fixture shall not serve as wet vents (10.16.5.b.1–5).
4. **Combination waste and vent.** A combination system requires special permission from the Board and is limited to floor drains and sinks. It is a wet-vented waste system without individual fixture-drain vents; every drainage pipe shall be at least two pipe sizes larger than required by 10.15 (10.16.1.a.1–3).

8.7 Stack Venting

1. **Highest branch interval.** Highest-level fixtures may enter a three-inch soil or waste stack whose continuation vents through the roof or reconnects to the vent system above the highest fixture. Each fixture shall enter independently; fixture wastes shall pitch no more than 1/4 inch per foot; toilet and bathtub/shower drains shall connect at the same floor level; and trap distances shall comply with Table 1 (10.16.6.a.1–2).
2. **Lower floors.** Where the required soil or waste stack under 10.16.2.a exists, the upward continuation of a toilet's vertical waste may be reduced to two inches and serve as the toilet vent and the waste for a lavatory, bathtub or shower, and kitchen sink (10.16.6.b; 10.16.Example.12).
3. **Back-to-back bathrooms.** Stack-vented bathroom groups may be back-to-back if they comply with 10.16.6.a (10.16.6.c).

8.8 Common Vents

1. **Same-level connection.** One vertically installed individual vent may serve two fixture traps when both fixture drains enter the vertical drain at the same level (10.16.7.a).
2. **Adjacent flat-bottom fixtures.** Two bathtubs or similar flat-bottom fixtures installed side-by-side

or back-to-back may share a vertical common vent (10.16.7.b).

3. **Different elevations.** Two fixtures in the same branch interval may share a vertical vent with connections no more than ten inches apart center-to-center. The vertical drain shall be one pipe diameter larger than the upper fixture drain and no smaller than the lower fixture drain; both wastes shall meet Table 1 (10.16.7.c.1–2).
4. **Back-to-back connection.** Two fixtures within Table 1 distances may share one continuous vent when each discharges separately into a double sanitary drainage tee with inlets at the same level (10.16.7.d).
5. **Two lavatories.** Two adjacent or back-to-back lavatories or similar fixtures within six feet of a main vented stack, proper wet vent, or continuous waste and vent may use one horizontal waste branch without an independent vent. The entire branch shall be at least two inches and both wastes shall enter its side center (10.16.7.e.1.a–b).

8.9 Circuit, Loop, and Bow Vents

1. **Battery arrangement.** Two through eight floor-outlet fixtures may enter the side center of a horizontal battery branch with a circuit or loop vent installed downstream of the last fixture connection (10.16.8.a).
2. **Circuit versus loop.** Connect a circuit vent to a proper vent upstream of the horizontal battery system; connect a loop vent to a proper vent downstream (10.16.8.a.1–2).
3. **Lower-floor relief.** On lower-floor battery branches, install a vertical relief vent downstream of the first fixture and reconnect to the circuit or loop vent. This relief is not required when only two fixtures are battery-wasted and vented on the branch (10.16.8.b, 10.16.8.b.1).
4. **More than eight fixtures.** Add a vent for each additional group of eight or fewer connected fixtures (10.16.8.b.2).
5. **Other outlet types.** Other fixtures may join the battery system but shall be individually or commonly vented (10.16.8.c, Fixtures Other Than the Floor Outlet Type).
6. **Parallel branches.** The battery rules apply to parallel branches, but each parallel horizontal branch shall be sized using 50% of the permitted horizontal-branch fixture-unit load (10.16.8.d and Exception).
7. **Battery takeoff.** Take the vent off at a vertical angle above the drain's centerline or from the top of the horizontal branch. The source repeats the letter c for this paragraph after d (10.16.8.c, Vent Connections).
8. **Bow vent.** A bow vent is permitted for an individual sink or lavatory when its vent cannot rise six inches above the flood-level rim before turning horizontal. Size it by Table 2 (10.16.9.a–b).

8.10 Relief Vents and Stack Offsets

1. **Small-angle offset.** If a horizontal branch connects within two feet above or below a stack offset of 45° or less from vertical, install a relief vent under 10.16.2.d (10.15.7.a).
2. **Large-angle offset.** In buildings five or more stories high, offsets greater than 45° from vertical require relief venting under 10.16.2.d. No horizontal branch shall connect to the offset or within two feet above or below it (10.15.7.b.4 and 10.15.7.b.4.a).
3. **Lower and upper sections.** Subject to 10.15, vent a large-angle offset as two stack sections: provide a relief vent continuing the lower section vertically, or a yoke vent between the offset and next lower branch; provide a yoke vent for the upper section (10.16.2.d.1.a.i–iii).
4. **Offset-vent size.** Offset vents shall be at least the smaller of the main-vent diameter and the soil/waste-stack diameter (10.16.2.d.1.a.iv).
5. **Above the highest branch.** An offset above the highest horizontal branch is in the stack vent and is considered for its effect on vent developed length (10.15.7.c).
6. **More than ten intervals.** Provide a relief vent at every tenth branch interval, counting downward from the top floor. Size it equal to the vent stack; connect its lower end by a wye below the floor's horizontal branch and its upper end to the vent stack by a wye at least three feet above the floor (10.16.2.f.1–3).
7. **Laundry suds relief.** Where laundries occupy more than three branch intervals, the required independent laundry system shall have a suds relief vent connecting to its main drain at least 40 pipe diameters downstream of the laundry-stack base and to a vent at least two branch intervals above that base. The inspector may permit a variation where conditions prevent compliance (10.15.8.d, 10.15.8.d.3–4).

8.11 Vent Sizing

1. **Individual vent minimum.** An individual vent shall be at least $1\frac{1}{4}$ inches and at least half the diameter of its connected drain (10.16.11.a).
2. **Battery relief minimum.** A relief vent on a battery-connected soil or waste branch shall be at least half that branch's diameter (10.16.11.b).
3. **Developed length.** Determine main-vent or vent-stack length from its lowest sanitary-drainage connection to the open air (10.16.11.c).
4. **Load and length.** Size vents by their developed length and total connected fixture units using Table 11. It applies to all vents except those specifically sized elsewhere in 248 CMR 3.00 through 10.00 (10.16.11.d).
5. **Selection procedure.** Compute fixture units from 10.15.Table.1 and 10.15.2.b, select the stack size using 10.15.Table.3 or Table.4 as appropriate, then select the vent size using Table 2. Follow the same procedure for soil/waste branch vents (10.16.Table.2, Note 1.a–c).
6. **Underground minimum.** Vent piping underground or below a basement floor shall be at least two inches (10.16.11.e).
7. **Future load.** Include future drainage provisions when determining final vent sizes (10.15.5).

Soil/waste diameter (in.)	Fixture units	Vent diameter (inches)									
		$1\frac{1}{4}$	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	4	5	6	8	10
$1\frac{1}{2}$	4	50	150	—	—	—	—	—	—	—	—
2	10	25	50	150	—	—	—	—	—	—	—
$2\frac{1}{2}$	28	—	30	100	300	—	—	—	—	—	—
3	7	—	42	150	360	1,040	—	—	—	—	—
3	21	—	32	110	270	810	—	—	—	—	—
3	53	—	27	94	230	680	—	—	—	—	—
3	102	—	25	86	210	620	—	—	—	—	—
4	43	—	—	35	85	250	980	—	—	—	—
4	140	—	—	27	65	200	750	—	—	—	—
4	320	—	—	23	55	170	640	—	—	—	—
4	530	—	—	21	50	150	580	—	—	—	—
5	190	—	—	—	28	82	320	990	—	—	—
5	490	—	—	—	21	63	250	760	—	—	—
5	940	—	—	—	18	53	210	640	—	—	—
5	1,400	—	—	—	16	49	190	590	—	—	—
6	500	—	—	—	—	33	130	400	1,000	—	—
6	1,100	—	—	—	—	26	100	310	780	—	—
6	2,000	—	—	—	—	22	84	260	660	—	—
6	2,900	—	—	—	—	20	77	240	600	—	—
8	1,800	—	—	—	—	—	31	95	240	940	—
8	3,400	—	—	—	—	—	24	73	190	720	—
8	5,600	—	—	—	—	—	20	62	160	610	—
8	7,600	—	—	—	—	—	18	56	140	560	—
10	4,000	—	—	—	—	—	—	31	78	310	960
10	7,200	—	—	—	—	—	—	24	60	240	740
10	11,000	—	—	—	—	—	—	20	51	200	630
10	15,000	—	—	—	—	—	—	18	46	180	570

Table 11. Size and lengths of vents. Source: 248 CMR 10.16.11, Table 2.

Dashes preserve blank cells. The 2023 table omits the heading identifying the length unit for its numerical body; its values are reproduced without adding a unit absent from that heading. Apply the table with 10.16.11.c–d and its Note 1.

8.12 Roof Terminals and Frost Closure

1. **Outside air.** Extend vent terminals above the roof to outside air and prevent obstruction or the return of sewage gases into the building (10.02.11).
2. **Ordinary terminal.** A through-roof vent extension shall be at least two inches and terminate 18 to 24 inches above the roof penetration (10.16.3.a.1).
3. **Occupied roof.** For gardening, parking, observation, or similar roof use, extend at least eight feet above the roof and increase one pipe diameter (10.16.3.a.2).

4. **Increaser.** Change the terminal diameter with an increaser at least one foot below the roof surface (10.16.3.a.3).
5. **Frost closure.** Where frost closure is likely, each through-roof vent extension shall be at least three inches (10.16.3.e).
6. **Building openings.** Do not terminate directly beneath a building opening or within ten feet horizontally of it unless at least two feet above its top (10.16.3.c.1).
7. **Forced-air intakes.** Provide 25 feet of horizontal separation. A terminal at least two feet above the intake top may be as close as ten feet; this paragraph expressly makes 10.16.3.a inapplicable in that case (10.16.3.c.2).
8. **Interior extensions.** Install soil, waste, and vent extensions inside the building. For remodeling or alterations only, the inspector may give prior permission for exterior vents when other means have been eliminated or are impractical (10.16.3.d).
9. **Flashing.** Make roof terminals watertight with proper flashing. Permitted flashing materials include lead, copper, aluminum, and other flashing materials; copper vent flashing shall weigh at least 12 ounces per square foot (10.16.3.b, 10.07.12.a, 10.06.2.a.4).
10. **Flange caps.** Extended roof-flange caps shall fit tightly inside the vent and not reduce the opening by more than the cap material's thickness (10.07.12.b).
3. **Identification.** Drip-connect and label each future connection "Future Vent" (10.16.12.c).

8.14 Sumps and Indirect-Waste Vents

1. **Sanitary sump.** A drain that cannot practically discharge by gravity shall discharge to a tightly covered, vented sump with automatic pumping (10.15.9.a).
2. **Sump vent sizing.** Size sanitary ejector-sump vents using Table 12. For multiple inlet drains, use an equivalent single diameter whose cross-sectional area equals the sum of their areas. The table's stated maximum pressure drop is one inch (10.16.13.a; 10.16.Table.3, Notes 1–2).
3. **Pneumatic ejector.** Its pressure-relief pipe shall vent independently through the roof and shall not join the ordinary vent system. Size it to relieve the ejector to atmospheric pressure within ten seconds, with a minimum diameter of one inch (10.16.13.b, 10.15.9.d.1–2).
4. **Individual fixture pumps.** Vent individual fixture pumps in accordance with their manufacturers' instructions (10.15.9.j.4).
5. **Indirect waste.** Permit free air circulation through indirect-waste piping. Provide a properly sized vent on a trapped waste branch; extend an indirect-waste stack serving two or more floors to outside air as required for a stack vent (10.12.5.e.1–3).
6. **Storm-vent labels.** A vent serving a trap through which clear-water waste enters the storm system shall be labeled "storm vent" at least every ten feet, at direction changes, and on both sides of partition, wall, ceiling, or roof penetrations (10.12.1.e.3.a–c).
7. **Subsoil-sump exception.** The sumps described for subsoil drains subject to backwater do not require vents (10.17.7.a.3).

8.13 Future Vent Connections

1. **Location.** Provide an accessible future vent connection at the lowest level of every building (10.16.12.a).
2. **Size.** Where a main vent stack is required, make the future connection full vent-stack size. In other buildings, including residential buildings, provide at least two inches (10.16.12.b).

Drain to sump (inches)	Vent diameter (inches)										
	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	4	5	6	8	10	12
2	23	52	290	—	—	—	—	—	—	—	—
$2\frac{1}{2}$	5	13	89	290	—	—	—	—	—	—	—
3	—	2	30	110	290	—	—	—	—	—	—
4	—	—	1	17	57	280	—	—	—	—	—
5	—	—	—	—	10	80	280	—	—	—	—
6	—	—	—	—	—	20	97	280	—	—	—
8	—	—	—	—	—	—	3	41	270	—	—
10	—	—	—	—	—	—	—	1	53	250	—
12	—	—	—	—	—	—	—	—	—	61	230

Table 12. Size and lengths of sump vents. Source: 248 CMR 10.16, Table 3.

Dashes preserve blank cells; the source does not print a length unit for the numerical body. For multiple drains use their combined cross-sectional area; the maximum stated pressure drop is one inch (Table 3, Notes 1–2). The reference to 10.16.14 in 10.16.13.a is inconsistent: this table follows 10.16.13 in the source.

9 Roof Drains

248 CMR 10.00, December 8, 2023 edition.

9.1 General Requirements

1. **Roof drain.** A roof drain receives water collected on a roof and conveys it into a leader or conductor (10.03, Roof Drain).
2. **Conductor and leader.** A conductor is inside the building and carries roof water to a storm drain or combined building sewer/storm sewer. A leader is an exterior pipe carrying water from roof or gutter drains to a storm-water waste system (10.03, Conductor; 10.03, Leader).
3. **Storm drainage.** A pipe receiving rain or surface water that enters a building or structure at any point is storm-water drainage piping; this includes area drainage and clear-water waste (10.17.1).
4. **Exterior scupper piping.** Storm leader piping originating at an outside scupper and never entering a building or structure is excluded from the definition of plumbing. This exemption applies to the piping, not connected fixtures or appurtenances (10.03, Plumbing.b, 10.03, Plumbing.d).
5. **Product acceptance.** All roof drains shall be product-accepted (10.17.11.a).
6. **Flat deck drains.** On normally serviced and maintained sun decks, parking decks, and similar areas, flat-surface drain assemblies may be level with the deck. Their available inlet area shall be at least twice the cross-sectional area of the connected conductor (10.17.11.b.2).
7. **Parking decks.** Roof drains serving vehicle parking decks or the outside top level of open parking garages shall discharge through an independent gas, oil, and sand interceptor/separator, then to the storm system or another approved disposal method. The paragraph prints a cross-reference to 10.09.1.b; the gas/oil separation provisions actually appear in 10.09.1.a (10.17.11.b.1; 10.09.1.a).
8. **Secondary drainage.** When installed, a secondary roof-drainage system shall discharge independently of the primary building storm system and terminate 18 to 60 inches above grade where building occupants can see it. It shall comply with all federal, state, and local codes (10.17.11.c).

9.2 Sizing and Capacity

1. **Horizontal sizing.** Size the building storm-drainage system, including every horizontal branch, by the maximum projected surface area served, using Table 1 below (10.17.3; 10.17.Table.1).
2. **Rainfall basis.** Table 1 is based on a maximum rainfall rate of four inches per hour (10.17.Table.1, Note 1).
3. **Vertical sizing.** Size vertical storm conductors by the maximum projected area drained, using Table 2 below (10.17.4; 10.17.Table.2).
4. **Short or shallow offsets.** Use the vertical-conductor table for offsets no more than 45° from vertical, and for offsets greater than 45° from vertical that are no longer than ten feet (10.17.10.b.1).
5. **Long offsets.** Use the horizontal-storm-drain table for offsets greater than 45° from vertical that exceed ten feet in length (10.17.10.b.2).
6. **Additional continuous flow.** When continuous or semi-continuous clear-water flow also enters the storm drain or sewer, count each gallon per minute as 24 square feet of roof area, based on four-inch rainfall (10.17.5).
7. **Uniform pitch.** Horizontal drainage shall have practical straight alignment and consistent uniform pitch. Pipe three inches or smaller requires at least 1/4 inch per foot; larger pipe requires at least 1/8 inch per foot (10.05.2.a–c).
8. **Engineered pitch exception.** Storm or sanitary piping may depart from those pitches if a Massachusetts professional engineer designs it for a computed discharge velocity of at least two feet per second (10.05.2.d).
9. **Siphonic systems.** A Massachusetts professional engineer is responsible for design and for ensuring that pipe sizing, dimensions, and installation meet the design. The plumbing inspector remains responsible for other code requirements, but need not approve the design or verify its specifications (10.17.3, Siphonic Roof Drainage Systems exception.a–c).

10.17 Table 1 — Size of Horizontal Storm Drains

Drain diameter (inches)	Maximum projected area (square feet)		
	1/8 inch/foot	1/4 inch/foot	1/2 inch/foot
3	—	1,160	1,644
4	1,880	2,650	3,760
5	3,340	4,720	6,680
6	5,350	7,550	10,700
8	11,500	16,300	23,000
10	20,700	29,200	41,400
12	33,300	47,000	66,600
15	59,500	84,000	119,000

The dash preserves a blank cell in the source; it is not a capacity of zero. Rainfall basis: four inches per hour (10.17.Table.1).

10.17 Table 2 — Vertical Conductors and Outside Leaders

Diameter (inches)	Maximum projected area (square feet)
2	720
2½	1,300
3	2,200
4	4,600
5	8,650
6	13,500
8	29,000

Table references: The source inconsistently cites both tables under 10.17.2. These notes identify them as 10.17.Table.1 and 10.17.Table.2; both appear on printed page 199.

9.3 Connections, Traps, and Cleanouts

- Separate systems.** Building sanitary and storm drainage shall be entirely separate. Storm water shall not enter a sewer intended only for sewage (10.17.2, 10.17.10.a.1).
- Combined sewer connection.** Where a combined sewer is available, the building storm sewer may join the building sanitary sewer in the same horizontal plane through one wye, forming a combined building sewer at least ten feet outside the inside face of the foundation wall (10.17.10.a.2).
- Low roofs on combined systems.** Conductors and storm drains serving low roofs shall be trapped when connected to a combined storm and sanitary system (10.17.9.a).
- Storm-only systems.** Traps are not required merely because a drain carries storm water to an exclusively storm-water system. The separate backflow requirement still applies where piping is subject to backflow (10.17.9.b, 10.17.8.a).
- Conductor trap size.** An individual conductor trap shall match the size of the horizontal drain to which it connects (10.17.9.c).
- Trap arrangement.** Install an individual trap in each conductor's storm-drain branch, or one trap in the main storm drain immediately before its combined-system connection (10.17.9.d.1).
- Trap cleanout.** Locate a conductor trap so that an accessible cleanout can be installed on its building side (10.17.9.d.2).
- Backflow exposure.** Roof, area, and clear-water waste piping subject to backflow shall have a back-water valve with a trap in an accessible location that is not subject to freezing (10.17.8.a).
- Base of conductor.** Provide a cleanout at or near the base of every vertical storm-water conductor (10.08.3.f).
- Roof-drain cleanout equivalent.** A readily removable roof-drain cover can satisfy the cleanout equivalent when its removal does not disturb concealed rough piping (10.08.3.m.3).

9.4 Roof Flashing and Freeze Protection

- Roof-drain flashing.** Roof drains passing into the building shall have watertight roof connections made

with proper flashing methods and materials. The code permits lead, copper, aluminum, or other flashing materials (10.17.11.b.3, 10.07.12.a).

2. **Vent flashing.** Every vent terminal shall be flashed watertight to the roof (10.16.3.b).
3. **Extended flange caps.** Caps for extended roof flanges shall fit tightly inside the vent pipe and shall not reduce its opening by more than the cap material's thickness (10.07.12.b).
4. **Copper vent flashing.** Sheet copper used for vent-terminal flashing shall weigh at least 12 ounces per square foot (10.06.2.a.4).
5. **Freeze protection.** Protect drainage piping exposed to freezing, including outside piping and piping in unheated areas, exterior walls, or unconditioned spaces. Protection and covering are the installing plumber's responsibility (10.05.7.b.1–2).
6. **Trap setting and freezing.** Set traps level relative to their water seals and protect them from freezing wherever necessary (10.08.2.f).

9.5 Vent Terminals Through Roofs

1. **Ordinary roof terminal.** A vent extension through a roof shall be at least two inches in diameter and terminate 18 to 24 inches above the roof penetration, subject to the special provisions below (10.16.3.a.1).
2. **Occupied roof.** For gardening, parking, observation, or similar roof use, extend the vent at least eight feet above the roof and increase it one pipe diameter (10.16.3.a.2).
3. **Enlargement below roof.** Make a vent-terminal diameter change with an increaser at least one foot below the roof surface (10.16.3.a.3).
4. **Frost closure.** Where frost closure is likely, each through-roof vent extension shall be at least three inches in diameter (10.16.3.e).
5. **Building openings.** A vent terminal shall not be directly beneath a building opening or within ten feet horizontally of it unless the terminal is at least two feet above the opening's top (10.16.3.c.1).
6. **Forced-air intakes.** Locate plumbing vent terminals at least 25 feet horizontally from forced-air intakes. A terminal at least two feet above the intake's top may be as close as ten feet. The source expressly states that 10.16.3.a does not apply in this case (10.16.3.c.2).
7. **Interior routing.** Soil, waste, and vent extensions shall be inside the building. Only for remodeling or alteration, exterior vents may be used after all other venting means have been eliminated or found impractical, with the inspector's prior permission (10.16.3.d).
8. **Header terminal size.** A header extension through the roof serving more than two four-inch soil or waste stacks shall be five inches in diameter; serving more than four four-inch stacks requires six inches (10.16.2.e.3–4).

10 Gas Pipe Sizing

10.1 Pipe Sizing Equations

In Revision 12/8/23 of CMR 10, the term ‘gas’ occurs 165 times. The term ‘pipe’ occurs 327 times. The combination ‘gas pipe’ occurs 0 times. Gas pipe sizing is covered by 248 CMR 4.00 and 5.00, including the adopted *NFPA 54/ANSI Z223.1*, Chapter 6, and Massachusetts amendments. The section and table numbers below follow the reproduced sources; an installation must use the applicable adopted edition and amendments.

In this, the reader is alerted that *where the pipe size is to be determined using any of the three methods in 6.1.1 through 6.1.3, the diameter of each pipe segment shall be obtained from the pipe sizing tables in Section 6.2 or Section 6.3 or from the sizing equations in Section 6.4.*

The so-called three methods are the (i) longest length method, (ii) branch length method, (iii) and hybrid pressure method. Each heuristic varies slightly from the others and each may return different answer for the same input.

There do exist other methods of gas pipe sizing, including the less-often used ‘pressure drop per 100 feet’ method. Things also get wooly when adding new fixtures to existing systems. A different permitted method may give a different answer, but it must still supply the full design demand at the required appliance inlet pressures.

Low Pressure Gas Formula

Appearing as item 6.4.1 is the *low pressure gas formula*, which describes gases below a gauge pressure of 1.5 psi, or approximately 10.3 kPa:

$$D = \frac{Q^{0.381}}{19.17 (\Delta H / (Cr \cdot L))^{0.206}} \quad (2)$$

In the above: (i) D is the inner diameter of the pipe measured in inches. (ii) Q is the volumetric flow rate through a pipe measured in cubic feet per hour at the formula’s reference conditions of 60°F and 30 in. Hg absolute pressure. (iii) ΔH is a pressure drop measured in inches of water column. (This is a confusing unit that we’ll have to take on below.) (iv) L is the equivalent pipe length in feet selected for the segment by the sizing method, including applicable fitting allowances. The numerical constants require the stated units.

The terms Cr , and as we’ll also see, Y are uncolorfully called *formula factors*. Natural gas has $Cr = 0.6094$ and $Y = 0.9992$. Undiluted propane has $Cr = 1.2462$ and $Y = 0.9910$.

High Pressure Gas Formula

A variation on the low pressure gas formula is the *high pressure gas formula*, used for gauge pressures of 1.5 psi

and above, or approximately 10.3 kPa and above:

$$D = \frac{Q^{0.381}}{18.93 ((P_1^2 - P_2^2) Y / (Cr \cdot L))^{0.206}} \quad (3)$$

The terms P_1 , P_2 are the respective upstream and downstream pressures, measured in psia (absolute pressure). Thus $P_{\text{abs}} = P_{\text{gauge}} + P_{\text{atm}}$; atmospheric pressure is approximately 14.7 psi at sea level. The same Q and L definitions apply.

One should feel suspicious when an equation contains any baked-in decimals, especially in exponents. It’s irresistible, then, to figure out where the low- and high pressure gas equations come from.

10.2 Derivation of Formulas

The equations for gas pipe sizing combine fluid mechanics with empirical flow correlations and unit conversions. To motivate their form, we first work within the *incompressible fluid* regime, in where the mass per unit volume is constant. This approximation is useful when gas density changes are small; the high pressure formula also accounts for compressibility. Going for a minimalist derivation, we lay out only the important terms in what follows. Here ρ is mass density, Q is actual volumetric flow at the local pipe conditions, and the equations use consistent units, such as SI. This Q must be converted before comparison with the reference-condition flow in the code formulas.

Hydraulic Diameter

Consider the motion of incompressible fluid through a straight pipe with cross sectional area A . For a notion of pipe diameter, define the *hydraulic diameter* D_H as

$$D_H = \frac{4A}{P},$$

where P is the wetted perimeter of the flow cross section. For a full circular pipe, this is the entire inner circumference. For the case of cylindrical pipes, we have

$$D_H = \frac{4\pi D^2}{4\pi D} = D,$$

which is just the circular diameter.

Volumetric Flow

Define the *flow area* A_W as the portion of the cross-sectional area occupied by the moving fluid, i.e. the water flowing on the bottom of a partially filled pipe. The *volumetric flow*, denoted Q , is defined as

$$Q = A_W \langle v \rangle,$$

where $\langle v \rangle = v$ is the mean velocity of the fluid over that area. Since gas occupies the entire cross section, we take $A_W = \pi D^2/4$. The inner wall area over length L is a different quantity, $S_W = \pi DL$.

Frictional Resistance

A model for the force of friction imposed on a moving fluid provides the formula

$$F_R = f' \times S_W \times v^2.$$

The coefficient f' has units of mass per volume; $f'v^2$ is the mean frictional force per unit wall area. Its value can depend on the flow and the pipe surface.

Bernoulli's Principle

A handy notion that we understand in terms of Newtonian laws and energy conservation is the famed *Bernoulli's principle*, stating that *along a streamline in steady, incompressible, frictionless flow, pressure plus kinetic and gravitational potential energy per unit volume remains constant*.

In the context of fluid moving through a pipe, one can expect that friction causes a loss of mechanical energy per unit volume, written as an equivalent pressure loss ΔP . For steady incompressible flow with no pump or turbine between the two points, one may write

$$P_1 + \frac{\alpha_1}{2} \rho v_1^2 + \rho g h_1 = \Delta P + P_2 + \frac{\alpha_2}{2} \rho v_2^2 + \rho g h_2,$$

which accounts for the kinetic, gravitational potential, and pressure terms from point '1' to point '2'. Here v_1, v_2 are mean velocities and α_1, α_2 correct for the velocity profiles. For a level pipe with unchanged area and velocity profile, $\Delta P = P_1 - P_2$.

Head Loss

A quantity

$$H_f = \frac{\Delta P}{\rho g},$$

called the *head loss* is used to characterize the drop in pressure along a length of pipe. Dimensionally, we have

$$[H_f] = \frac{\text{kg m}}{\text{s}^2 \text{m}^2} \frac{\text{m}^3 \text{s}^2}{\text{kg m}} = \text{m},$$

i.e. pressure loss is expressed as a length of the flowing fluid. When ρ is gas density, H_f is gas head. The water-column pressure drop used in the gas tables is instead $\Delta H = \Delta P/(\rho_{\text{water}}g)$, with ρ_{water} here denoting water's mass density. One inch of water column is approximately 249 Pa, or 0.0361 psi.

Darcy-Weisbach Equation

The effect of friction on a fluid moving in a pipe is characterized by the dimensionless *Darcy friction factor*, denoted f . To motivate this, consider steady, fully developed incompressible flow with mean velocity v through a straight, level circular pipe of cross-sectional area A . With unchanged momentum flux between its ends, we use Newton's second law to establish

$$A\Delta P - F_R = 0,$$

or after simplifying,

$$H_f = \frac{f'}{\rho g} \frac{4}{D} L v^2.$$

The combination f'/ρ is dimensionless, which we take as proportional to the coefficient of friction for fluid moving through the pipe. To keep consistent with common literature on the topic, define

$$f = \frac{8f'}{\rho}$$

so the above is finally written

$$H_f = f \frac{L}{D} \frac{v^2}{2g},$$

known as the Darcy-Weisbach equation.

In terms of volumetric flow, the same equation is written

$$H_f = f \frac{8L}{\pi^2 g} \frac{Q^2}{D^5}.$$

If solving for the diameter of pipe involved, one has:

$$D = \left(\frac{f}{H_f} \frac{8L}{\pi^2 g} \right)^{1/5} Q^{2/5} \quad (4)$$

With f still to be determined, equation (4) motivates the low pressure dependence in Equation (2); it does not by itself derive the numerical code constants or the compressible-flow dependence in Equation (3). In general f depends on Reynolds number and relative roughness, so solving for D can require iteration.

Laminar Flow (Optional)

For steady, fully developed laminar flow of a Newtonian fluid through a circular pipe, the Darcy friction factor is

$$f = \frac{64}{\text{Re}},$$

where Re is the *Reynold's number*, defined as

$$\text{Re} = \frac{\rho D}{\mu} \langle v \rangle,$$

where μ is the dynamic viscosity of the fluid.

Engineering Fudge Factors

In terms of Q , H_f , L , the diameter of the pipe, according to Darcy-Weisbach via Equation (4), can be written

$$D = A \times Q^{0.4} H_f^{-0.2} L^{0.2},$$

where A is a factor not depending on Q , H_f , L only if f and the fluid properties are held fixed. This A is a coefficient, not the cross-sectional area used above.

Taking, for instance, the low pressure gas formula and comparing exponents, we see 0.381 in place of 0.4, and 0.206 in place of 0.2. These differences can arise from the dependence of friction on flow. For example, assuming $f \propto \text{Re}^{-0.15}$ with fixed fluid properties gives $\text{Re} \propto Q/D$ and

$$H_f \propto LQ^{1.85} D^{-4.85},$$

hence

$$D \propto Q^{1.85/4.85} H_f^{-1/4.85} L^{1/4.85}.$$

The exponents are approximately 0.3814, -0.2062 , and 0.2062 . This illustrates the form; it does not establish the complete code correlation. The high pressure formula depends on $P_1^2 - P_2^2$, which arises in compressible-flow models where gas density varies with absolute pressure. It does not follow from a constant-density assumption.

10.3 Fixture Demand

The reason we concern about gas pipe sizing is to supply enough fuel to each consuming fixture at the required inlet pressure while avoiding unnecessary oversizing and waste.

For pipe sizing, a gas fixture's 'demand' is characterized by its maximum rated fuel input, measured in British thermal units per hour. Note that energy over time is formally equivalent to 'power'.

In the following we list several natural gas-consuming fixtures with the respective energy consumption rate. Numeric values are hashed together from a variety of teaching and real-world sources. All are subject to change. These are illustrative inputs; use the appliance nameplate or manufacturer's maximum input for sizing. Unless a permitted diversity allowance applies, add the maximum inputs of all appliances served. (The term 'domestic' is abbreviated as 'dom.')

- Dryer (clothing, dom.) (30-35 kBtu/hr)
- Fireplace (direct vent.) (30-40 kBtu/hr)
- Furnace (100 kBtu/hr)

- Hydronic boiler (dom.) (100-120 kBtu/hr)
- Pool Heater (285 kBtu/hr)
- Stove (freestanding range, dom.) (65 kBtu/hr)
- Water Heater (40 gal. dom.) (35-40 kBtu/hr)
- Water Heater (50 gal. dom.) (50 kBtu/hr)

Calorific Value

Gas-consuming fixtures are usually characterized by energy consumption rate in British thermal units per hour. However this information is often reported as the volume of gas consumed in cubic feet per hour (cfh). To convert between the amount of energy (Btu) in a gas and the cubic-foot volume (ft^3) of the gas, one needs to know the *calorific value* of the gas.

By a conspiracy between engineers and God, it just happens that the calorific value of natural gas is about one thousand British thermal units per cubic foot:

$$\text{C.V. of natural gas} \approx 1000 \text{ Btu/ft}^3$$

For this reason, we can use the same numerical value for kBtu/hr and ft^3/hr when the heating value is taken as 1000 Btu/ ft^3 . The units themselves are different. Of course, the calorific value depends on gas composition and the reference conditions for volume. The value 1000 is an assumption for these examples; use the gas supplier's value on the same volume basis as the sizing table.

Such a shortcut doesn't work for other gases such as propane, or even natural gas under different conditions. Some texts and manuals use the calorific value of 1100 Btu/ ft^3 . Using this, we may convert some number X Btu/hr into a volumetric flow Y by writing:

$$Y = \frac{X \text{ Btu/hr}}{1100 \text{ Btu/ft}^3} = \frac{X \text{ ft}^3}{1100 \text{ hr}}$$

10.4 Schematics

Any gas distribution system can be represented in a diagram, usually two-dimensional, much like a schematic for an electric circuit. The so-called pipe sizing schematic contains at least one point of delivery for gas service, along with all gas-consuming fixtures represented as locations.

Connecting the point(s) of service to all fixtures is a network of pipes represented as lines as shown in Figure 7.

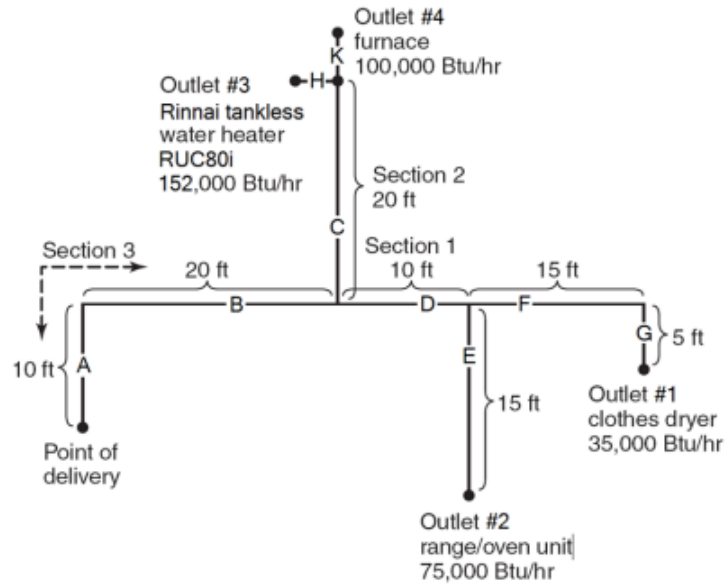


Figure 7. Sample gas distribution schematic. (*Rinnai Technical Bulletin 111-1/2". Gas Line Piping Information.* ^a)

^aAll Information was obtained from National Fuel Gas Code, NFPA54, ANSI Z223.1.

It's not clear whether the Rinnai company originated the diagram published. The *2010 Oregon Mechanical Specialty Code*, in Appendix C-A, offers a suspiciously similar schematic shown in Figure 8.

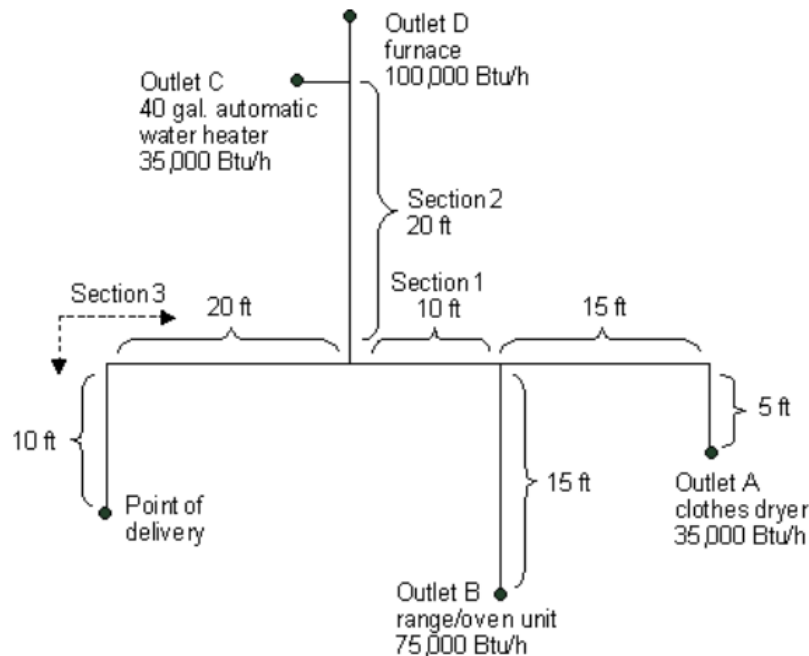


Figure 8. Sample gas distribution schematic. (*2010 Oregon Mechanical Specialty Code. Figure C-A.7.1. Piping Plan Showing a Steel Piping System*)

A very similar diagram appears in the literature of El Dorado County, California as shown in Figure 9. The engineers responsible for these diagrams must have cheated off the same guy.

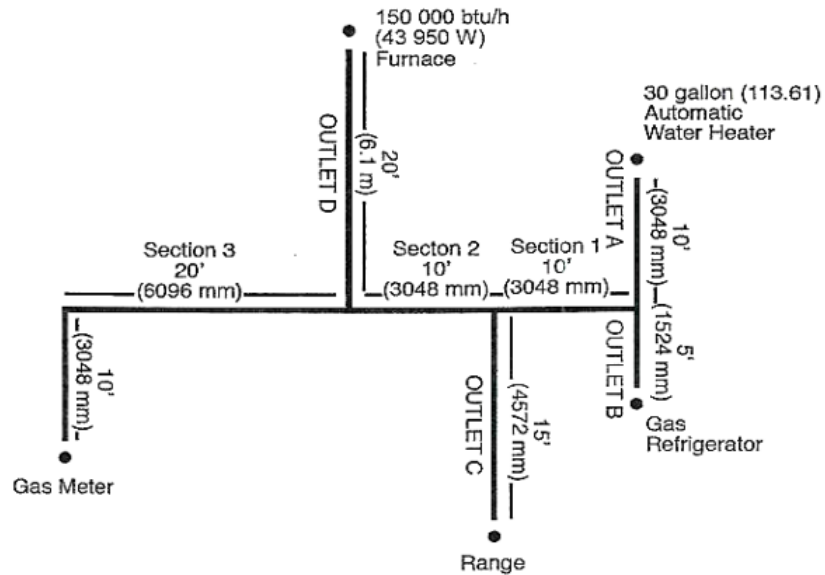


Figure 9. Sample gas distribution schematic. (*El Dorado County, CA. GAS PIPE LINE CALCULATION SIZING. Figure A*)

Some new symbols for the gas meter, distribution manifold, shut-off valve, and pressure regulator are shown in Figures 10-11. In each Figure, the fixture demands are listed in cubic feet per hour rather than British thermal units per hour. (Beware this difference!)

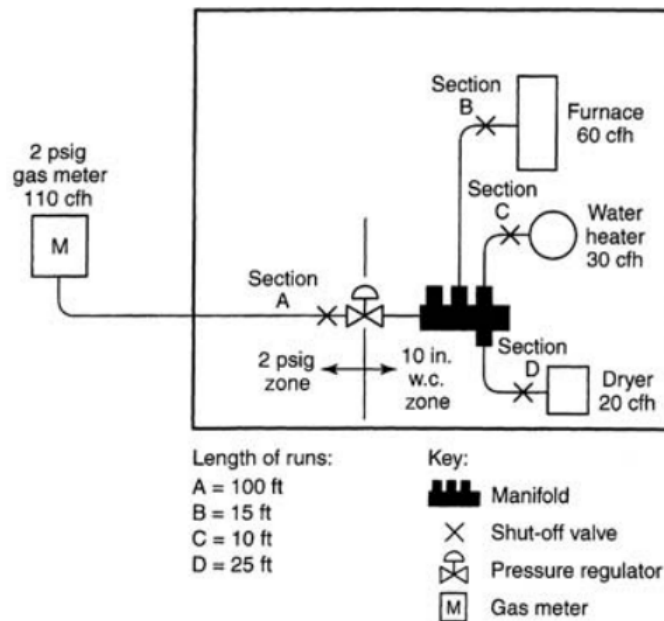


Figure 10. Sample gas distribution schematic. (*2010 Oregon Mechanical Specialty Code. Figure C-A.7.2. Piping Plan Showing a CSST System*)

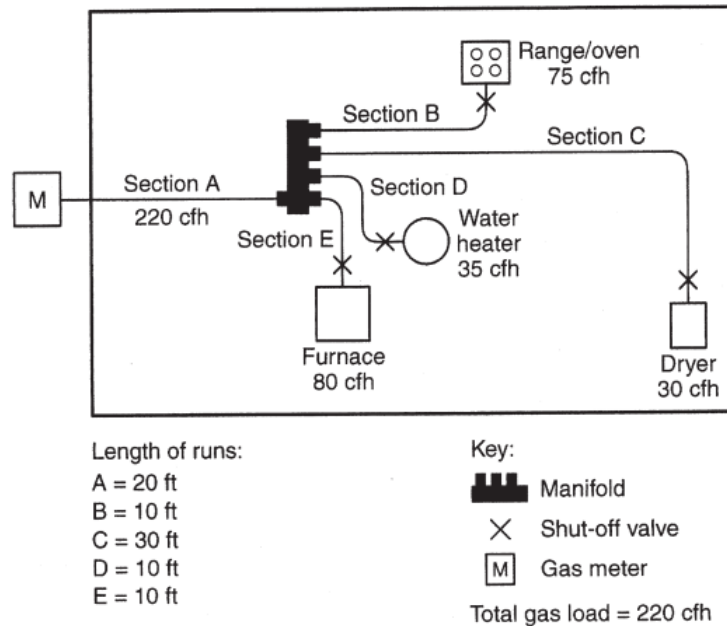


Figure 11. Sample gas distribution schematic. (2010 Oregon Mechanical Specialty Code. Figure C-A.7.3. Piping Plan Showing a Copper Tubing System)

10.5 Preparing a Schematic

When confronted with a gas pipe sizing problem, the diagram is everything. However, these may be handed to you with too much or too little information on the page. To make a clean preparation, let us do some edits on Figure 8 (example alpha) and Figure 9 (example beta).

For starters, ignore any extraneous information such as ‘section’ number. The point of delivery is denoted M (for meter) with an arrow indicating direction of flow as shown in Figures 12, 13.

Label all Fixtures (A, B, C, ...)

If not present in the schematic, write the resource demand in ft^3/hr or kBtu/hr of each fixture. Each fixture, or ‘outlet’, should take a unique label such as A, B, C, etc.

Label all Tees (X, Y, Z, ...)

It also helps to label each tee connection in the system with a different grouping of letters than those reserved for

fixtures. For these, it suffices to use the labels X, Y, Z, etc.

Label the Meter (M)

Apart from ‘M’ standing for ‘meter’, it’s convenient that ‘M’ stands in the middle of the alphabet, dividing fixtures (A, B, ...) from tees (X, Y, ...).

Turns and Couplings

For our purposes, there is no need to label any ninety-degree connections or similar. The pipe diameter is assumed constant across such fittings.

Elbows, valves, etc. introduce friction even when there are only a few. Follow the selected table’s fitting allowance or include their equivalent lengths as required. In a sentence, the effect of a given accessory is characterized by the some length of pipe that would impose the same pressure loss as the accessory at the same flow. Unless stated otherwise, the exercises below use the shown developed lengths without additional fitting lengths, as an explicit simplification.

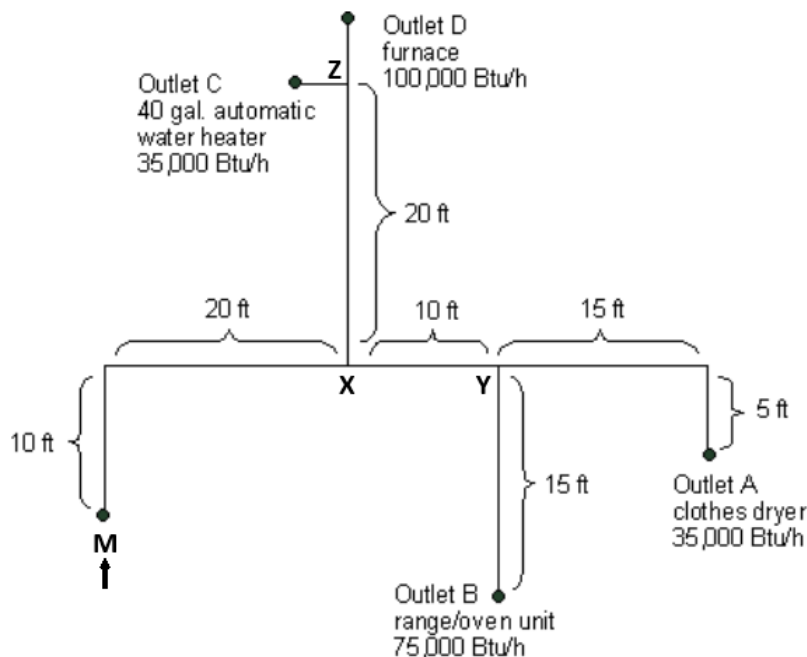


Figure 12. Example alpha: Sample schematic (Figure 8) prepared for pipe sizing.

Worksheet alpha				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Y using ?	-	-
B	55	75 from Y using ?	-	-
C	50	35 from Z using ?	-	-
D	50	100 from Z using ?	-	-
M	0	-	245 to X	-
X	30	245 from M using ?	110 to Y	135 to Z
Y	40	110 from X using ?	35 to A	75 to B
Z	50	135 from X using ?	35 to C	100 to D

Table 13. Example alpha worksheet: Representation of Figure 12.

Prepare Worksheet

Before choosing any sizing method, it's helpful to determine all pertinent lengths and flow rates throughout the system. This can be done on the schematic itself, however we'll develop the habit of capturing schematics like Figure 12 in worksheet form as shown. (Note fixtures C and D are each directly connected to Z. For this example, the two connections beyond Z are assumed to have negligible length, so each outlet is taken as 20 ft from X.)

Reading the worksheet, one observes:

- The worksheet encodes the essential information on the schematic.
- The objective is to turn question marks (?) into pipe diameters in inches.

- The 'Input', 'Out 1', and 'Out 2' columns are reported in ft^3/hr , i.e. cfh.
- The sum of all fixture inputs equals the meter output.
- For a given tee connection, the input equals the sum of the outputs.
- The words 'to' and 'from' occur in equal numbers.
- The input to the meter and the output from each fixture is ignored.

Performing a similar task on the second example (beta) gives rise to Figure 13 and the corresponding worksheet:

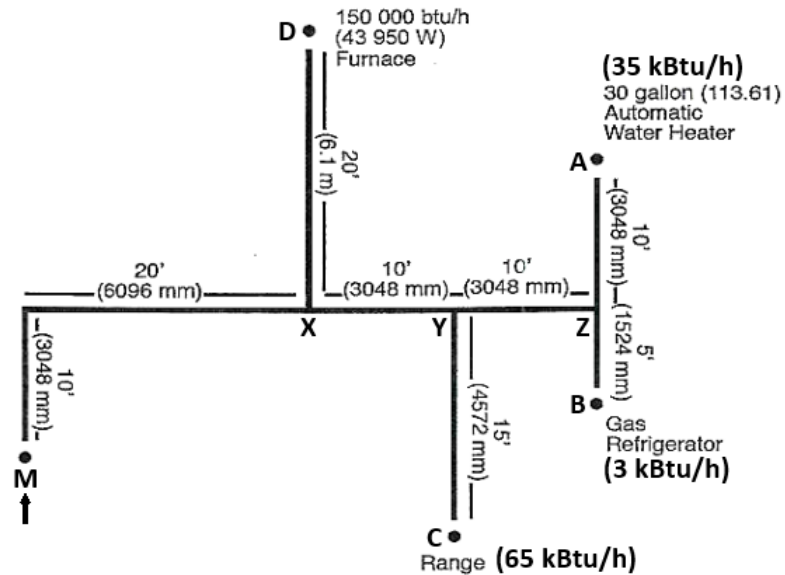


Figure 13. Example beta: Sample schematic (Figure 9) prepared for pipe sizing.

Worksheet beta				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Z using ?	-	-
B	55	3 from Z using ?	-	-
C	55	65 from Y using ?	-	-
D	50	150 from X using ?	-	-
M	0	-	253 to X	-
X	30	253 from M using ?	150 to D	103 to Y
Y	40	103 from X using ?	65 to C	38 to Z
Z	50	38 from Y using ?	35 to A	3 to B

Table 14. Example beta worksheet: Representation of Figure 13.

To prepare another schematic (example gamma), we turn to the *Plumbing-Heating-Cooling Contractors of Massachusetts*, or *PHCC*, for a study guide called *Introduction: PSI Exams*. Figure 14 contains a gas pipe sizing problem adapted from Slide 291. All fixtures, tees, and pipe lengths are labeled.

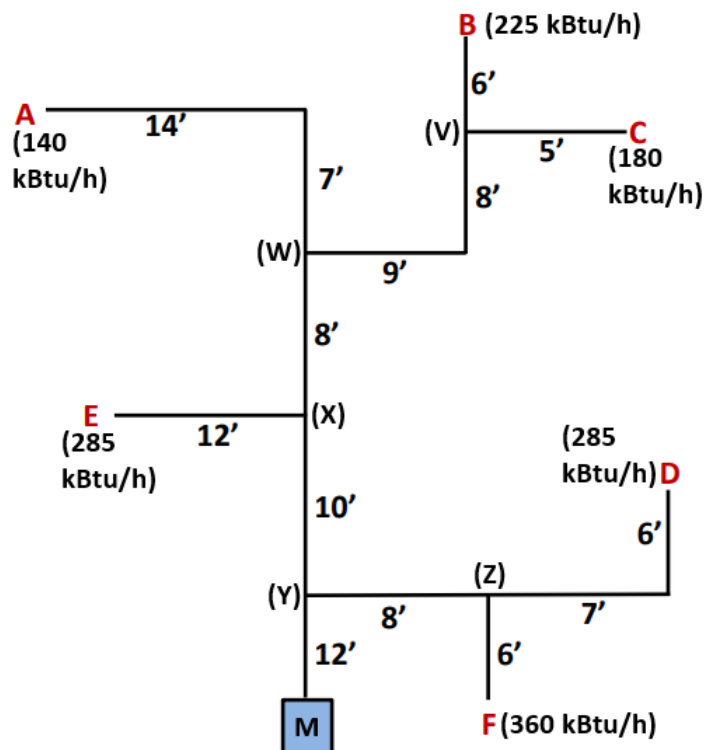


Figure 14. Example gamma: Sample schematic prepared for pipe sizing. Adapted from *PHCC. Introduction: PSI Exams. Slide 291*.

Worksheet gamma				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	51	140 from W using ?	-	-
B	53	225 from V using ?	-	-
C	52	180 from V using ?	-	-
D	33	285 from Z using ?	-	-
E	34	285 from X using ?	-	-
F	26	360 from Z using ?	-	-
M	0	-	1475 to Y	-
V	47	405 from W using ?	225 to B	180 to C
W	30	545 from X using ?	140 to A	405 to V
X	22	830 from Y using ?	285 to E	545 to W
Y	12	1475 from M using ?	830 to X	645 to Z
Z	20	645 from Y using ?	285 to D	360 to F

Table 15. Example gamma worksheet: Representation of Figure 14.

In each example above (alpha, beta, gamma), take the heating value as 1000 Btu/ft³ when converting the diagram loads to cfh, and assume all pipes carry natural gas under conditions consistent with *ANSI Z223.1*, Table 6.2(b). Schedule 40 Metallic Pipe. (See Figure 15.)

10.6 Pipe Sizing Charts

Throughout *ANSI Z223.1* are various pipe sizing charts for natural gas in various conditions. The reason for hav-

ing charts is to save the plumber from directly applying Equations (2) and (3) in the field.

Table 6.2.1(j) Semirigid Copper Tubing												
INTENDED USE: Tube Sizing Between House Line Regulator and the Appliance.												
Nominal:	Tube Size (in.)											
	K & L:	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/4	1 1/2	2	
ACR:	1/4	1/4	1/2	1/2	3/4	3/4	1 1/8	1 1/8	1 3/8	1 3/4	2 1/4	
Outside:	0.375	0.500	0.625	0.750	0.875	1.125	1.375	1.625	1.875	2.125	2.400	
Inside:	0.305	0.402	0.527	0.652	0.745	0.995	1.245	1.481	1.717	1.953	2.189	
Length (ft)	10	39	80	162	283	402	859	1,550	2,440	5,080		
	20	27	55	111	195	276	590	1,060	1,680	3,490		
	30	21	44	89	156	222	474	853	1,350	2,800		
	40	18	38	77	134	190	406	730	1,150	2,400		
	50	16	33	68	119	168	359	647	1,020	2,130		

Figure 16. Sample from *ANSI Z223.1*, Chapter 6. Table 6.2.1(j). Semirigid Copper Tubing.

10.7 Longest Length Method

Quoting directly from *ANSI Z223.1*, Chapter 6, the longest length method is stated as:

The pipe size of each section of gas piping shall be determined using the longest length of piping from the point of delivery to the most remote outlet and the load of the section.

Implementing the longest length method goes as follows:

1. Determine which fixture is furthest distance from the meter in developed length. This is the so-called longest length. (This is also the last time you count distances to fixtures in this method.)
2. Determine the total ft^3/hr demand of each fixture and of the whole system. (Convert from kBtu/hr if necessary.)
3. In the appropriate Table such as 6.2(b), read down the left column until finding the longest length from Step 1. Use the next longer listed length if necessary; never round the required length down.
4. Staying in the longest length row, read across the Table until finding the total ft^3/hr demand from Step 2. Choose the first capacity equal to or greater than that demand.
5. At this step you're pointing at one cell in the body of the Table. The header of the column indicates the diameter of the gas pipe leaving the meter.
6. All other pipe sizes are derived from the *same* row in the Table. To size any given pipe segment, determine the total demand of all fixtures supplied through that segment and read the Table as done in Steps 3-5.
7. Tip: Deal with all fixtures first. Then treat tee fittings as if they're fixtures.

Worked Example: Alpha

Apply the longest length method to example alpha represented in Figure 12. The two pipes leaving Z are assumed to have negligible length.

Referencing the Figure (namely the worksheet beneath it), the longest length corresponds to outlet A at 60 ft from meter. The total demand of the system is $245 \text{ ft}^3/\text{hr}$. (Steps 1 and 2.)

Looking in the Table 6.2(b) for a length of 60 ft and a demand of $245 \text{ ft}^3/\text{hr}$ leads to the cell labeled $257 \text{ ft}^3/\text{hr}$. The header of this column indicates 1 inch. The pipe diameter leaving the meter is 1 inch. (Steps 3, 4, and 5.)

In ft^3/hr , the fixtures A, B, C, D receive 35, 75, 35, 100 respectively. Staying in the 60 ft row of the Table, we straightforwardly read off the diameters going to each fixture. In inches, the results are 1/2, 3/4, 1/2, 3/4.

The tee labeled X receives $245 \text{ ft}^3/\text{hr}$. Looking in the Table for a length of 60 ft and a demand of $245 \text{ ft}^3/\text{hr}$ leads to the cell labeled $257 \text{ ft}^3/\text{hr}$. The header of this column indicates 1 inch. The pipe diameter entering X from M is 1 inch.

The tee labeled Y receives $110 \text{ ft}^3/\text{hr}$. Looking in the Table for a length of 60 ft and a demand of $110 \text{ ft}^3/\text{hr}$ leads to the cell labeled $137 \text{ ft}^3/\text{hr}$. The header of this column

indicates 3/4 inch. The pipe diameter entering Y from X is 3/4 inch.

The tee labeled Z receives 135 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 135 ft³/hr leads to the cell labeled 137 ft³/hr. The header of this column

indicates 3/4 inch. The pipe diameter entering Z from X is 3/4 inch.

All pipes are now sized and the problem is solved. The updated worksheet is as follows:

Worksheet alpha: Longest length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Y using 1/2 in	-	-
B	55	75 from Y using 3/4 in	-	-
C	50	35 from Z using 1/2 in	-	-
D	50	100 from Z using 3/4 in	-	-
M	0	-	245 to X	-
X	30	245 from M using 1 in	110 to Y	135 to Z
Y	40	110 from X using 3/4 in	35 to A	75 to B
Z	50	135 from X using 3/4 in	35 to C	100 to D

Worked Example: Beta

Apply the longest length method to example beta represented in Figure 13.

Referencing the Figure (namely the worksheet beneath it), the longest length corresponds to outlet A at 60 ft from meter. The total demand of the system is 253 ft³/hr. (Steps 1 and 2.)

Looking in the Table 6.2(b) for a length of 60 ft and a demand of 253 ft³/hr leads to the cell labeled 257 ft³/hr. The header of this column indicates 1 inch. (Steps 3, 4, and 5.) The pipe diameter leaving the meter is 1 inch.

In ft³/hr, the fixtures A, B, C, D receive 35, 3, 65, 150 respectively. Staying in the 60 ft row of the Table, we straightforwardly read off the diameters going to each fixture. In inches, the results are 1/2, 1/2, 1/2, 1.

The tee labeled X receives 253 ft³/hr. Looking in the

Table for a length of 60 ft and a demand of 253 ft³/hr leads to the cell labeled 257 ft³/hr. The header of this column indicates 1 inch. The pipe diameter entering X from M is 1 inch.

The tee labeled Y receives 103 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 103 ft³/hr leads to the cell labeled 137 ft³/hr. The header of this column indicates 3/4 inch. The pipe diameter entering Y from X is 3/4 inch.

The tee labeled Z receives 38 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 38 ft³/hr leads to the cell labeled 65 ft³/hr. The header of this column indicates 1/2 inch. The pipe diameter entering Z from Y is 1/2 inch.

From this point we get to cheat the rest. All pipe diameters downstream of Y are 1/2 inch.

Worksheet beta: Longest length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Z using 1/2 in	-	-
B	55	3 from Z using 1/2 in	-	-
C	55	65 from Y using 1/2 in	-	-
D	50	150 from X using 1 in	-	-
M	0	-	253 to X	-
X	30	253 from M using 1 in	150 to D	103 to Y
Y	40	103 from X using 3/4 in	65 to C	38 to Z
Z	50	38 from Y using 1/2 in	35 to A	3 to B

Worked Example: Gamma

Apply the longest length method to example gamma represented in Figure 14.

Referencing the Figure (namely the worksheet beneath it), the longest length corresponds to outlet B at 53 ft from meter. The total demand of the system is 1475 ft³/hr. (Steps 1 and 2.)

Looking in the Table 6.2(b) for a length of 60 ft and a demand of 1475 ft³/hr leads to the cell labeled 1520 ft³/hr. The header of this column indicates 2 inch. (Steps 3, 4, and 5.) The pipe diameter leaving the meter is 2 inch. Therefore segment MY is 2 inch.

In ft³/hr, the fixtures A, B, C, D, E, F receive 140, 225, 180, 285, 285, 360, respectively. Staying in the 60 ft row of the Table, we straightforwardly read off the diameters going to each fixture. In inches, the results are 1, 1, 1, 1.25, 1.25, 1.25.

The tee labeled V receives 405 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 405 ft³/hr leads

to the cell labeled 528 ft³/hr. The header of this column indicates 1.25 inch. The pipe diameter entering V from W is 1.25 inch.

The tee labeled W receives 545 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 545 ft³/hr leads to the cell labeled 791 ft³/hr. The header of this column indicates 1.5 inch. The pipe diameter entering W from X is 1.5 inch.

The tee labeled X receives 830 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 830 ft³/hr leads to the cell labeled 1520 ft³/hr. The header of this column indicates 2 inch. The pipe diameter entering X from Y is 2 inch.

The tee labeled Z receives 645 ft³/hr. Looking in the Table for a length of 60 ft and a demand of 645 ft³/hr leads to the cell labeled 791 ft³/hr. The header of this column indicates 1.5 inch. The pipe diameter entering Z from Y is 1.5 inch.

All pipes are now sized and the problem is solved. The updated worksheet is as follows:

Worksheet gamma: Longest length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	51	140 from W using 1 in	-	-
B	53	225 from V using 1 in	-	-
C	52	180 from V using 1 in	-	-
D	33	285 from Z using 1.25 in	-	-
E	34	285 from X using 1.25 in	-	-
F	26	360 from Z using 1.25 in	-	-
M	0	-	1475 to Y	-
V	47	405 from W using 1.25 in	225 to B	180 to C
W	30	545 from X using 1.5 in	140 to A	405 to V
X	22	830 from Y using 2 in	285 to E	545 to W
Y	12	1475 from M using 2 in	830 to X	645 to Z
Z	20	645 from Y using 1.5 in	285 to D	360 to F

ProblemsProblem 25

Let A, B, C, D represent gas-consuming fixtures that operate under conditions consistent with Table 6.2(b). In particular:

- A = Furnace (100 kBtu/hr)
- B = Water heater (40 kBtu/hr)

Answer: Longest length 62 ft, round up to 70 ft.

- A: 100 from X using 3/4 in
- X: 200 from M using 1 in

- C = Dryer (30 kBtu/hr)

- D = Fireplace (30 kBtu/hr)

Assume the calorific value of natural gas is 1000 Btu/ft³. If the system is arranged according to the following worksheet, calculate all pipe diameters using the longest length method.

- Y: 100 from X using 3/4 in
- All other diameters 1/2 in.

Longest length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	22	100 from X using ?	-	-
B	21	40 from Y using ?	-	-
C	28	30 from Z using ?	-	-
D	62	30 from Z using ?	-	-
M	0	-	200 to X	-
X	14	200 from M using ?	100 to A	100 to Y
Y	16	100 from X using ?	40 to B	60 to Z
Z	22	60 from Y using ?	30 to C	30 to D

Problem 26

For systems that tolerate a pressure drop of 0.3 in. w.c. instead of 0.5, the Table we've been using must be replaced with Table 6.2(a), shown in Figure 17.

Table 2: (Schedule 40 Metallic Pipe)					Gas:		Natural	
					Inlet Pressure:		Less than 2 psi	
					Pressure Drop:		0.3 in. w.c.	
					Specific Gravity:		0.6	
N/A: A flow of less than 10 cfh; All table entres round to 3 significant digits; BTUH = CFH X 1000								
	Pipe Size (in)							
Moninal:	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3
Actual ID:	0.622	0.824	1.049	1.380	1.610	2.067	2.469	3.068
Length (ft)	Capacity in Cubic Feet of Gas per Hour (CFH)							
10	131	273	514	1060	1580	3050	4860	8580
20	90	188	353	726	1090	2090	3340	5900
30	72	151	284	583	873	1680	2680	4740
40	62	129	243	499	747	1440	2290	4050
50	55	114	215	442	662	1280	2030	3590
60	50	104	195	400	600	1160	1840	3260
70	46	95	179	368	552	1060	1690	3000
80	42	89	167	343	514	989	1580	2790
90	40	83	157	322	482	928	1480	2610
100	38	79	148	304	455	877	1400	2470

Figure 17. Sample from ANSI Z223.1, Chapter 6. Table 6.2(a). Schedule 40 Metallic Pipe.

Let A, B, C, D, E represent gas-consuming fixtures that operate under conditions consistent with Table 6.2(a). In particular:

- A = Furnace (100 kBtu/hr)
- B = Water heater (40 kBtu/hr)
- C = Dryer (30 kBtu/hr)

- D = Fireplace (30 kBtu/hr)
- E = Stove (65 kBtu/hr)

Assume the calorific value of natural gas is 1000 Btu/ft³. If the system is arranged according to the following worksheet, calculate all pipe diameters using the longest length method.

Answer: Longest length 40 ft.

- A: 100 from W using 3/4 in
- B: 40 from W using 1/2 in
- C: 30 from Y using 1/2 in

- D: 30 from Z using 1/2 in
- E: 65 from Z using 3/4 in
- W: 140 from X using 1 in
- X: 265 from M using 1.25 in

Longest length method (using Table 6.2(a))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	32	100 from W using ?	-	-
B	30	40 from W using ?	-	-
C	28	30 from Y using ?	-	-
D	40	30 from Z using ?	-	-
E	37	65 from Z using ?	-	-
M	0	-	265 to X	-
W	26	140 from X using ?	100 to A	40 to B
X	16	265 from M using ?	140 to W	125 to Y
Y	23	125 from X using ?	30 to C	95 to Z
Z	28	95 from Y using ?	30 to D	65 to E

- Y: 125 from X using 3/4 in
- Z: 95 from Y using 3/4 in

10.8 Branch Length Method

Quoting directly from *ANSI Z223.1*, Chapter 6, the branch length method is stated as:

1. Pipe size of each section of the longest pipe run from the point of delivery to the most remote outlet shall be determined using the longest run of piping and the load of the section.
2. The pipe size of each section of branch piping not previously sized shall be determined using the length of piping from the point of delivery to the most remote outlet in each branch and the load of the section.

Implementing the branch length method goes as follows:

1. Choose a fixture and determine its distance from the meter in developed length. (This number changes per fixture.)
2. Determine that fixture's demand in ft^3/hr . (Convert from kBtu/hr if necessary.)
3. In the appropriate Table such as 6.2(b), read down the left column until finding the length from Step 1. Use the next longer listed length if necessary; never round the required length down.

In Example alpha, the results attained by the branch length method are the same as those attained with the longest length method.

In Example beta, all results agree with the longest

4. Staying in the length row, read across the Table until finding the total ft^3/hr demand from Step 2. Choose the first capacity equal to or greater than that demand.

5. At this step you're pointing at one cell in the body of the Table. The header of the column indicates the diameter of the gas pipe serving the fixture.

6. Repeat for all fixtures.

7. Treat tee fittings as if they're fixtures with the following extra rule: size the segment feeding a tee for its total downstream demand, using the full meter-to-outlet length to the most remote outlet downstream of that tee.

The branch length method involves more fiddling with pipe lengths in the schematic. This process can get woolly, thus it's strongly recommended to generate a worksheet or mark the schematic with all pertinent information. In particular (reiterating Step 7), **the effective distance from any tee fitting to the meter must include the distance to the most remote outlet downstream of the fitting.**

Reworked Examples

Let us rework Examples alpha, beta, gamma using the branch length method. The additions in parentheses below extend each tee's meter distance to its most remote downstream outlet; they are not extra pipe lengths or fitting allowances. Starting with the same worksheets under Figures 12, 13, 14, use Steps 1-7 to reason:

length method with one exception, and that is the pipe size leading to outlet D. To double check, we have that outlet D is 50 ft from the meter while demanding $150 \text{ ft}^3/\text{hr}$, which, according to the branch length method, requires 3/4 inch

Worksheet alpha: Branch length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Y using 1/2 in	-	-
B	55	75 from Y using 3/4 in	-	-
C	50	35 from Z using 1/2 in	-	-
D	50	100 from Z using 3/4 in	-	-
M	0	-	245 to X	-
X	30 (+30)	245 from M using 1 in	110 to Y	135 to Z
Y	40 (+20)	110 from X using 3/4 in	35 to A	75 to B
Z	50 (+0)	135 from X using 3/4 in	35 to C	100 to D

Worksheet beta: Branch length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	60	35 from Z using 1/2 in	-	-
B	55	3 from Z using 1/2 in	-	-
C	55	65 from Y using 1/2 in	-	-
D	50	150 from X using 3/4 in	-	-
M	0	-	253 to X	-
X	30 (+30)	253 from M using 1 in	150 to D	103 to Y
Y	40 (+20)	103 from X using 3/4 in	65 to C	38 to Z
Z	50 (+10)	38 from Y using 1/2 in	35 to A	3 to B

pipe as calculated. This number came out to 1 inch using in the 60 ft row.
the longest length method, namely because we were trapped

Problems

Problem 27

Let A, B, C, D, E represent gas-consuming fixtures that operate under conditions consistent with Table 6.2(b). In particular:

- A = Pool heater (250 kBtu/hr)
- B = Boiler (100 kBtu/hr)

- C = Fireplace (30 kBtu/hr)
- D = Stove (65 kBtu/hr)
- E = Water heater (40 kBtu/hr)

Assume the calorific value of natural gas is 1000 Btu/ft³. If the system is arranged according to the following worksheet, calculate all pipe diameters using the branch length method.

Answer: The run to A is 163 ft, so A and the pipe feeding W use the 175 ft row of the full Table. That row is outside the cropped Figure; its capacities for nominal 1, 1.25, 1.5, and 2 inch pipe are 144, 296, 443, and 854 cfh, respectively.

- A: 250 from W using 1.25 inch
- B: 100 from X using 3/4 inch
- C: 30 from Y using 1/2 inch
- D: 65 from Z using 1/2 inch
- E: 40 from Z using 1/2 inch
- W: 485 from M using 2 inch
- X: 235 from W using 1 inch
- Y: 135 from X using 3/4 inch
- Z: 105 from Y using 3/4 inch

Worksheet gamma: Branch length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	51	140 from W using 1 in	-	-
B	53	225 from V using 1 in	-	-
C	52	180 from V using 1 in	-	-
D	33	285 from Z using 1 in	-	-
E	34	285 from X using 1 in	-	-
F	26	360 from Z using 1 in	-	-
M	0	-	1475 to Y	-
V	47 (+6)	405 from W using 1.25 in	225 to B	180 to C
W	30 (+23)	545 from X using 1.5 in	140 to A	405 to V
X	22 (+31)	830 from Y using 2 in	285 to E	545 to W
Y	12 (+41)	1475 from M using 2 in	830 to X	645 to Z
Z	20 (+13)	645 from Y using 1.25 in	285 to D	360 to F

Branch length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	163	250 from W using ?	-	-
B	28	100 from X using ?	-	-
C	38	30 from Y using ?	-	-
D	44	65 from Z using ?	-	-
E	54	40 from Z using ?	-	-
M	0	-	485 to W	-
W	13 (+150)	485 from M using ?	250 to A	235 to X
X	18 (+36)	235 from W using ?	100 to B	135 to Y
Y	28 (+26)	135 from X using ?	30 to C	105 to Z
Z	34 (+20)	105 from Y using ?	65 to D	40 to E

Problem 28

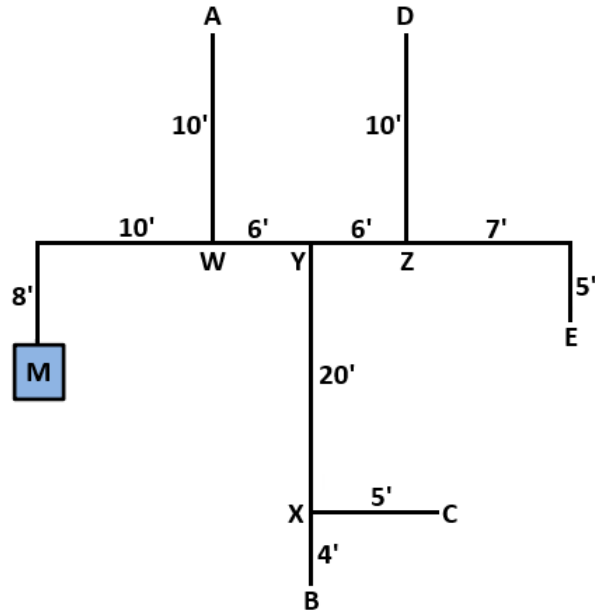
Let A, B, C, D, E represent gas-consuming fixtures that operate under conditions consistent with Table 6.2(b). In particular:

- A = Stove (65 kBtu/hr)
- B = Furnace (100 kBtu/hr)
- C = Water heater (40 kBtu/hr)
- D = Dryer (30 kBtu/hr)

- E = Fireplace (30 kBtu/hr)

Assume the calorific value of natural gas is 1000 Btu/ft³.

The system is depicted in the accompanying Figure. Distances not to scale. For the longest length method and the branch length method, generate worksheets representing the schematic and size the system. The sizes below agree for both methods. The longest length method uses 49ft, rounded to the 50ft row, throughout; the parenthesized distances show the branch length method.



Longest length or Branch length method (using Table 6.2(b))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
A	28	65 from W using 1/2 in	-	-
B	48	100 from X using 3/4 in	-	-
C	49	40 from X using 1/2 in	-	-
D	40	30 from Z using 1/2 in	-	-
E	42	30 from Z using 1/2 in	-	-
M	0	-	265 to W	-
W	18 (+31)	265 from M using 1 in	65 to A	200 to Y
X	44 (+5)	140 from Y using 3/4 in	100 to B	40 to C
Y	24 (+25)	200 from W using 1 in	140 to X	60 to Z
Z	30 (+12)	60 from Y using 1/2 in	30 to D	30 to E

Problem 29

Consider the system depicted in Figure 11. Ignoring the effect of any shut-off valves, the central player in the schematic is a manifold, denoted X, which is essentially a tee with many branches.

The system is to be piped with semirigid copper tubing sustaining a pressure drop at 1 in. w. c. The gas has a specific gravity of 0.60 and the calorific value of the gas is 1000 Btu/ft³. Assume an inlet gauge pressure below 2 psi, sufficient to permit the stated drop while meeting the

appliance inlet requirements.

Given the material and conditions, it is warranted to size the system using Table 6.2.1(j) as depicted in Figure 16. Create an appropriate worksheet and size the system using the branch length method.

Answer: For the effective distance to X, use 20 ft plus the distance to the furthest outlet, i.e. 30 ft, giving 50 ft altogether. All tubing sizes below use the nominal K and L row of the Table, not the outside-diameter row.

Branch length method (using Table 6.2.1(j))				
Symbol	From Meter (ft)	Input (cfh)	Out 1 (cfh)	Out 2 (cfh)
B	30	75 from X using 1/2 in	-	-
C	50	30 from X using 3/8 in	-	-
D	30	35 from X using 3/8 in	-	-
E	30	80 from X using 1/2 in	-	-
M	0	-	220 to X	-
X	20 (+10)	220 from M using 1 in	75 to B	-
X	20 (+30)	-	30 to C	-
X	20 (+10)	-	35 to D	-
X	20 (+10)	-	80 to E	-

10.9 Other Sizing Methods

There are several ways to solve the gas pipe sizing problem, but arguably the longest length method and branch length method are the most practical in the field.

For a system with higher- and lower-pressure distribution zones separated by a line pressure regulator, as sketched in Figure 10, the **Hybrid pressure method** sizes the zones separately. Use the longest delivery-to-regulator length for the higher-pressure zone, and the longest regulator-to-outlet length for each lower-pressure zone. An appliance regulator alone does not establish a hybrid distribution system. Select each zone's allowable drop from its actual supply and required downstream pressures.

There also exists the **Pressure drop per 100 feet**

method. This method allocates the available pressure drop along the piping, using each segment's flow demand and length. The tabulated pressure drop is an absolute difference in inches of water column per 100 feet of pipe. Figure 18 gives gas capacities for combinations of that pressure drop and pipe size. For a segment of length L_i , a tabulated drop $\Delta H_{100,i}$ over 100 feet gives

$$\Delta H_i = \Delta H_{100,i} \frac{L_i}{100 \text{ ft}}.$$

Include applicable fitting losses and check that the summed drops along every delivery-to-appliance path stay within its available pressure drop. The capacities in this Figure are thousands of Btu/h, as stated in its caption.

PRESSURE DROP PER 100 FEET IN INCHES W.C.	PIPE SIZES (inch)					
	1/2	3/4	1	1 1/4	1 1/2	2
0.2	31	64	121	248	372	716
0.3	38	79	148	304	455	877
0.5	50	104	195	400	600	1160
1.0	71	147	276	566	848	1640

Figure 18. Sample gas distribution schematic. (2010 Oregon Mechanical Specialty Code. Table C-A.3.4. Thousands of Btu/h (MBTU) of Natural Gas per 100 Feet of Pipe at Various Pressure Drops and Pipe Diameters)

Finally, one can use the **direct application of Equations (2), (3)** for low- or high-pressure gas. Use them with the appropriate sizing method and equivalent length for smooth-wall pipe or tubing, then select a listed size with sufficient actual inside diameter. They do not replace manufacturer-specific sizing data for CSST.

In many situations, natural gas may be treated as *ideal gas*. The same approximation applies to air used for a pressure test. If a sealed, isolated piping system containing a fixed amount of air cools from a warm afternoon to a chilled morning, its pressure decreases according to the

ideal gas law:

$$PV = NKT$$

Here P is absolute pressure, T is absolute temperature (kelvin when K is in SI units), N is the number of molecules, and K is Boltzmann's constant. With V , N , K constant and the gas at uniform temperature, it follows that

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} .$$

Convert gauge readings to absolute pressure before using this ratio. A measured drop can also result from leakage; this relationship alone does not establish the cause.

11 Residential Water Heaters: Service and Troubleshooting

11.1 Purpose and General Service Method

These notes are organized primarily by **complaint and symptom**, rather than by manufacturer or heater type. The goal is to move from the customer's complaint to a reliable diagnosis, then decide whether the proper response is adjustment, repair, cleaning, replacement of a component, or replacement of the heater.

A useful general service sequence is:

1. Identify the complaint precisely.
2. Identify the heater type and energy source.
3. Inspect for leakage, corrosion, unsafe conditions, and obvious installation defects.
4. Check static water pressure where relevant.
5. Operate one or more fixtures and reproduce the complaint.
6. Measure temperatures, pressures, voltage, resistance, gas operation, or flow as appropriate.
7. Determine whether the problem is hydraulic, electrical, combustion-related, control-related, venting-related, or a failure of the tank itself.
8. Repair the actual cause rather than the component nearest the symptom.
9. Confirm proper operation under actual demand before leaving.

11.2 Basic Heater Identification

Before troubleshooting, record enough information to understand what system is being serviced: tank or tankless; gas, propane, electric, heat pump, or indirect; atmospheric vent, power vent, direct vent, or condensing; tank capacity; input rating in BTU/hr or watts; model and serial number; approximate age; water connection size; gas connection size, where applicable; electrical voltage and circuit size, where applicable; presence of expansion tank; presence of mixing valve; and presence of recirculation system.

11.3 No Hot Water

Initial Checks

Confirm that the complaint is truly no hot water rather than insufficient hot water; check whether all fixtures are affected; confirm that the heater has water and that shutoff

valves are open; check whether the heater is attempting to operate; and check for a hot-to-cold crossover elsewhere in the plumbing system.

Electric Tank Heater

Possible causes include: breaker off or tripped; no line voltage at heater; tripped high-limit control; failed upper thermostat; failed upper heating element; and loose or burned wiring.

Suggested diagnostic order:

1. Verify voltage at the heater.
2. Check the high-limit control.
3. Check the upper thermostat.
4. Check the upper element for resistance and leakage to ground.
5. Continue to the lower circuit if necessary.

For a resistive element,

$$R = \frac{V^2}{P}.$$

For example, a 4500 W element at 240 V should measure approximately

$$R = \frac{240^2}{4500} \approx 12.8 \, \Omega.$$

Never energize a standard immersion element unless the tank is completely full of water.

Gas Tank Heater

Possible causes include: gas supply off; pilot out; failed thermocouple or thermopile; failed igniter; flame-sensing failure; failed gas control valve; combustion-air problem; venting problem; and safety lockout.

For power-vent equipment, follow the operating sequence:

1. Call for heat
2. Blower starts
3. Pressure switch proves draft
4. Ignition begins
5. Gas valve opens
6. Burner lights
7. Flame is proven

The point where the sequence stops often identifies the failed component or condition.

Tankless Heater

Possible causes include: insufficient flow to activate heater; dirty inlet screen; failed flow sensor; ignition failure; gas supply issue; electrical supply issue; vent obstruction; condensate blockage; and control or sensor fault.

11.4 Hot Water Runs Out Too Quickly

Possible causes include: failed lower electric element; failed lower thermostat; broken or deteriorated dip tube; sediment accumulation; heater undersized for actual demand; increased household demand; mixing valve problem; recirculation problem; and hot-to-cold crossover.

Useful Checks

Measure stored-water temperature and delivered-water temperature; determine whether the heater fully recovers; check whether the lower electric element operates; look for excessive draw from large fixtures; shut off the cold supply to suspect mixing fixtures to test for crossover; and consider dip-tube failure when water starts hot and quickly becomes lukewarm.

11.5 Water Is Not Hot Enough

Possible causes include: thermostat or gas control set too low; failed thermostat; failed heating element; excessive demand; mixing valve adjusted incorrectly or malfunctioning; hot-to-cold crossover; sediment or scale; tankless heater operating beyond its temperature-rise capacity; low gas input; and very cold incoming water.

Do not assume the heater is defective until actual tank temperature and delivered fixture temperature have both been checked.

11.6 Water Is Too Hot

Possible causes include: thermostat set too high; failed thermostat or gas control; electric thermostat not seated tightly against tank; heating element remaining energized; and failed or incorrectly adjusted mixing valve.

Excessive temperature is both a scald hazard and a possible cause of relief-valve discharge.

11.7 Water Around the Heater

Water on the floor does not automatically mean that the tank is leaking.

Possible Sources

Failed tank; drain valve; cold-water connection; hot-water connection; T&P relief valve; T&P discharge piping; expansion tank or its connection; nearby plumbing; condensate from high-efficiency equipment; condensate from HVAC equipment above the heater; flue condensation; and condensation on cold piping.

Diagnostic Approach

1. Dry the area.
2. Inspect from the top down.
3. Check threaded and soldered connections.
4. Check the T&P outlet and discharge piping.
5. Observe the heater through a complete heating cycle.
6. Check system pressure before and during heating if thermal expansion is suspected.
7. Confirm whether water is emerging from the tank shell itself.

An internal pressure-vessel leak generally means replacement of the heater.

11.8 T&P Relief Valve Dripping or Discharging

Do not assume that a leaking relief valve is itself defective.

Possible causes include: thermal expansion; excessive incoming water pressure; excessive water temperature; defective relief valve; debris on the valve seat; and a valve that opened and no longer reseats properly.

Service Checks

Check static water pressure; check pressure while the heater is firing or recovering; check actual hot-water temperature; determine whether the plumbing system is closed; check expansion tank condition and precharge; and inspect the relief valve only after system conditions have been evaluated.

A relief valve should not be replaced as the sole repair when excessive pressure or temperature caused it to open.

11.9 Thermal Expansion and Pressure Problems

When water is heated, it expands.

In an open system, some expansion may move backward toward the supply. In a closed system, a check valve, backflow preventer, pressure-reducing valve, or similar device may prevent this movement.

Possible results include: pressure rise during each heating cycle; T&P valve dripping; faucet and cartridge damage; premature failure of plumbing components; and intermittent high-pressure complaints.

Expansion Tank Checks

Confirm that an expansion tank is present where required; check whether it is waterlogged; check air-side precharge with water pressure removed from the tank; compare precharge to normal system pressure; and verify proper sizing and location.

11.10 Noisy Heater

Gas Tank Heater

Rumbling or popping commonly suggests sediment on the bottom of the tank.

Sediment may cause: poor heat transfer; local boiling beneath deposits; rumbling or popping; reduced effective tank capacity; and longer recovery time.

Electric Tank Heater

Noise may be associated with: scale on heating elements; sediment; expansion or contraction of piping; and loose electrical components.

11.11 Discolored, Smelly, or Poor-Quality Hot Water

Possible causes include: corrosion products; anode deterioration; bacterial activity; sediment; water chemistry; and deteriorating piping rather than the heater itself.

Rotten-egg odor may involve sulfate-reducing bacteria, water chemistry, and magnesium-anode reactions.

Do not remove an anode permanently without considering the effect on tank life.

11.12 Slow Recovery

Possible causes include: failed lower electric element; low-voltage condition; incorrect element wattage; heavy sediment; low gas input; dirty burner; poor combustion; scale in heat exchanger; and heater undersized for load.

Compare actual recovery performance with the heater's rating rather than relying only on the customer's impression.

11.13 Electric Tank Heater Troubleshooting

Main Components

Upper thermostat; upper heating element; lower thermostat; lower heating element; high-limit control; and wiring and junction box.

Element Testing

With power safely disconnected: measure resistance across the element; compare with expected resistance from rated voltage and wattage; test each element terminal to ground; and any continuity to ground indicates a failed element.

Common Patterns

Common patterns. No hot water usually points first to power, the high limit, upper thermostat, or upper element. Some hot water but poor capacity commonly points to the lower thermostat or lower element. Water that is too hot suggests a thermostat or wiring problem. A tripping breaker suggests a grounded element, shorted wiring, or a circuit problem. Slow recovery suggests element wattage, low voltage, sediment, or a failed element.

11.14 Gas Tank Heater Troubleshooting

Standing-Pilot Systems

Check: gas supply; pilot flame; thermocouple or thermopile output; burner ignition; main gas control; combustion air; and vent draft.

Electronic-Ignition Systems

Check the sequence of operation and determine where the sequence stops.

Possible faults include: igniter; flame sensor; pressure switch; blower; gas valve; control board; vent obstruction; and condensate blockage.

11.15 Drafting, Venting, and Combustion Problems

Possible warning signs include: soot; melted plastic near draft hood; rust near flue connection; exhaust smell; repeated burner shutdown; condensation; and spillage at draft hood.

Check: vent connection; vent sizing; chimney condition; combustion-air openings; obstructions; negative building pressure; and common venting with other appliances.

Power-vent, direct-vent, and condensing vent systems must be checked against the appliance manufacturer's installation requirements.

11.16 Tankless Water Heater Troubleshooting

Common complaints include: no hot water; water becomes cold during low flow; temperature fluctuates; insufficient hot-water temperature; heater shuts down under heavy demand; and error codes.

Common causes include: low fixture flow; dirty inlet screen; failed flow sensor; scale in heat exchanger; gas supply undersized; vent restriction; condensate restriction; sensor failure; and mixing or crossover problem.

A tankless heater is primarily limited by its heating rate. Greater flow and greater required temperature rise demand more input.

11.17 Heat-Pump Water Heater Troubleshooting

Check: air filter; airflow; room temperature; condensate drainage; fan operation; compressor operation; resistance backup elements; operating mode; and fault codes.

A complaint of slow recovery may be normal in heat-pump-only mode if demand exceeds the heat pump's recovery rate.

11.18 Indirect Water Heater Troubleshooting

Possible faults include: boiler not firing; failed aquastat or sensor; failed circulator; failed zone valve; airlocked boiler loop; fouled heat exchanger or coil; and control wiring problem.

Separate the domestic-water side from the boiler-side problem before replacing components.

11.19 Tank and Internal Component Failures

Sediment

Sediment can: reduce effective storage volume; insulate the heat source from the water; cause noise; make draining difficult; and cover lower electric elements.

Dip Tube

A failed dip tube can cause incoming cold water to mix near the top of the heater, producing hot water initially followed by rapid cooling.

Anode Rod

The sacrificial anode protects exposed tank steel.

Inspect or replace where practical when heater condition justifies the work.

Tank Failure

Evidence may include: water leaking from tank shell; rust streaking from seams; leakage from beneath jacket not traceable to fittings; and severe corrosion.

A failed pressure vessel is generally not repaired in the field. Replace the heater.

11.20 Repair Versus Replace

Typical repair decisions. Heating elements, thermostats, thermocouples, flame sensors, and drain valves are normally repair items. A gas control may be worth repairing if the heater's age and condition justify it. A dripping T&P valve should be diagnosed before replacement so excessive pressure or temperature is not overlooked. Expansion tanks may be recharged or replaced as appropriate. A dip tube may be repaired when worthwhile. Heavy internal corrosion or a leaking tank shell generally means replacing the heater. Repeated failures on an old heater, or an expensive tankless component, should be weighed against the heater's age, condition, remaining service life, and replacement cost.

Age alone should not determine replacement. Consider condition; repair cost; availability of parts; evidence of corrosion; efficiency; venting condition; installation deficiencies; and likelihood of additional near-term failures.

11.21 Replacement Survey

Before obtaining a replacement heater, record fuel type; tank capacity; input rating; first-hour rating where relevant; voltage and circuit size; vent type; vent diameter; heater height; heater diameter; available access; water connection locations; gas connection location; drain or pan arrangement; T&P discharge arrangement; expansion tank condition; existing mixing valve; recirculation connection; gas piping size; electrical supply; and chimney or vent condition.

11.22 Water Heater Replacement Procedure

Before Removal

1. Confirm that the heater itself actually requires replacement. Trace water before condemning a tank; leaking unions, nipples, drain valves, T&P valves, expansion tanks, condensate lines, and nearby equipment can all put water beneath a heater.
2. Record the existing heater's fuel, capacity, input, voltage, vent type, connection sizes, dimensions, and model information.

3. Compare the replacement heater with the existing installation before removing anything. Verify height, diameter, connection locations, vent requirements, electrical requirements, gas input, condensate requirements, clearances, and service access.
4. Note existing installation defects. Replacement is a good opportunity to correct bad shutoffs, unsupported piping, bad venting, missing expansion control, poor T&P discharge piping, or other deficiencies rather than simply copying the old installation.
5. Shut off the energy source. For an electric heater, open the breaker or disconnect and verify the heater is de-energized. For a gas heater, shut off the appliance gas cock.
6. Shut off the cold-water supply to the heater.

Drain the Old Heater

1. Connect a hose to the drain valve and route it to a safe point of discharge.
2. Open a hot-water faucet. This admits air so the tank can drain instead of pulling a vacuum.
3. Open the heater drain valve.
4. If little or no water comes out, sediment may be blocking the drain opening. Verify pressure has been relieved before attempting to clear or remove a clogged valve.
5. Allow the tank to drain enough that it can be moved safely.

Disconnect and Remove

1. Disconnect the hot and cold water connections.
2. Disconnect gas piping, electrical wiring, venting, condensate piping, recirculation piping, and controls as applicable.
3. Make disconnected utilities safe while work is underway.
4. Remove the heater.
5. Inspect the pan, floor, stand, drain, wall, chimney or vent connector, expansion tank, shutoff valves, and nearby piping before setting the replacement.

Set and Pipe the New Heater

1. Set the new heater level and in the required position.
2. Connect the cold inlet and hot outlet.
3. Reconnect any recirculation piping, mixing valve, drain pan, condensate piping, and related water-side components.
4. Install the T&P relief valve and discharge piping as required by the heater listing and applicable code.
5. Install or reconnect the thermal-expansion tank where required. Check its air precharge before putting the system under water pressure.
6. Reconnect gas, venting, or electrical wiring as applicable, but do not energize electric heating elements yet.

Fill the Tank and Purge Air

The tank must be completely full before an electric element is energized. Purging also prevents a large pocket of compressed air from remaining in the hot-water system.

1. Leave at least one hot-water faucet open before turning the cold supply back on. A high or distant hot fixture is useful because it gives displaced air an easy path out of the system.
2. Slowly open the cold-water supply valve to the heater.
3. Water entering through the cold inlet and dip tube fills the tank from the bottom upward. As the water level rises, the air in the tank is forced out through the hot outlet and the open faucet.
4. At first, the faucet will usually spit and sputter air and water. Let it run.
5. Continue filling until the hot faucet produces a solid, steady stream without significant bursts of air. At that point the tank is essentially full.
6. Open the remaining hot-water fixtures one at a time and run each until sputtering stops. This clears air trapped in branch piping.
7. Check every disturbed water connection while the system is under full pressure.
8. For an electric tank, do not restore power until a steady stream of water has been obtained from the hot side and the tank is known to be full. Dry-firing an immersion element can destroy it very quickly.

A small amount of residual air may continue to appear at fixtures after replacement. Continue running the hot side until normal, smooth flow is restored.

Gas Heater Startup

1. Reconnect the gas piping and leak-test every disturbed joint.
2. Reconnect the vent system and verify the proper diameter, support, pitch, clearances, and termination for the appliance.
3. Follow the manufacturer's lighting or startup procedure.
4. Observe the complete ignition sequence and burner operation.
5. On an atmospheric heater, verify that the draft hood is drafting and that flue gases are not spilling into the room after the vent has had time to establish draft.
6. On a power-vent or condensing heater, verify blower operation, pressure-switch proving, vent flow, and condensate drainage.

Electric Heater Startup

1. Confirm one more time that the tank is full.
2. Verify electrical connections and the correct supply voltage.
3. Replace access covers and insulation as required.
4. Restore power.
5. Verify element operation or current draw where practical.
6. Allow the heater to recover and confirm that the thermostats cycle normally.

Final Checks After Replacement

1. Check all water joints again after the heater has warmed and the piping has expanded.
2. Check gas joints again where applicable.
3. Verify burner, element, blower, compressor, or heat-pump operation as applicable.
4. Verify venting and combustion on fuel-fired equipment.
5. Verify condensate drainage on condensing and heat-pump equipment.
6. Check static water pressure and confirm that thermal expansion is controlled.
7. Verify the T&P valve and its discharge piping.
8. Allow adequate recovery time, then measure delivered hot-water temperature.
9. Run actual fixtures and confirm normal performance under demand.

11.23 Final Service Checklist

Before leaving: no active water leaks; no gas leaks; correct electrical operation; correct burner operation; proper venting; proper condensate drainage where applicable; proper T&P discharge arrangement; acceptable static and dynamic water pressure; expansion control functioning; correct delivered hot-water temperature; heater cycles normally; and customer complaint has been reproduced and resolved.