## 3.1 Plumbing System

### Introductory Remarks

Plumbers in working Massachusetts must follow the State *Plumbing Code* to ensure the safe and adequate operation of finished plumbing systems. Formally called *248 CMR 10.00*, the *Uniform State Plumbing Code* is available via *mass.gov* as PDF. Edition 12/8/23 is used for the majority of this study.

*Fixture Unit - Definition*

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*:

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<u>Fixture Unit</u>. One cubic foot of water drained in a 1.25 inch pipe over a period of one minute. One cubic foot of water is equal to 7.5 gallons.

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The definition provided is alarmingly vague. Whether (or not) one cubic foot of water *actually* drains through a 1.25 inch diameter pipe in precisely one minute is questionable. Needless to mention, one cubic foot is closer to 7.4813 gallons of liquid. As 7.5 has two digits of precision, the writer may as well have stated the pipe is 1.3 inches in diameter.

Despite the definition, there is enough information to crudely solve for the velocity $v$, if uniform, of the water in the 1.25 inch diameter pipe. Assuming the pipe is cylindrical and the water fills the cross section, a straightforward exercise in kinematics tells us the velocity is:

$$v = 23.5 \frac{\text{in}}{\text{sec}} = 117 \frac{\text{ft}}{\text{min}}$$

Once again, one should be wondering if a $\approx 7.5$ gallon slug of water is actually moving through a pipe at about two feet per second. One can readily imagine factors that could offset this number, i.e. the effects of gravity and the roughness of the interior.

One can also imagine the preceding observations as being pedantic, or perhaps unfairly picky, especially when plumbers are compensated for their labors rather than theories. On the other hand, students of plumbing should expect - and deserve - something better than the State-provided definition of the fixture unit. (The story gets worse before it gets better.)

*Fixture Unit - Dimensionality*

Given the definition, 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 10.00 or comparable resources, one instead finds that fixture units are *not measured in physical units*, but are instead always *dimensionless* scale factors like 3, $\pi$, or 1000. This is also troublesome for the definition, because we lack three numbers to balance the units of gallons, minutes, and inches.

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

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<u>Load Factor</u>. 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.

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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 10.00. It will turn out, however, that probability theory is at the heart of what a fixture unit *is*.

*Fixture Unit - Alternate Definitions*

Reaching for the *Uniform Plumbing Code*, *IAMPO/ANSI 1 - 2021*, one finds a more honest yet similarly vague word salad explaining the fixture unit:

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<u>Fixture Unit</u>. 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.

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We finally encounter a sensible definition of the fixture unit in the *International Plumbing Code*, *ICC A117.1-2017*, which reads:

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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.

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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 technical debt by skewering the definition of the fixture unit, and the intent here is not to solve the problems with the definition stated in CMR 10.00 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 warm-up exercise called the **Valve and Tank Problem**. This problem is informed by a mixture of real data and more-or-less made up numbers corresponding to likeliness of occurrence, type of occupancy, etc., of certain plumbing fixtures.

Next, we deploy a **Deconvoluted 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 10.00.

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.

## 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.

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 number $k$ at which $P(k) \approx 1\%$. (v) Calculate the final water demand using $k$.

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 Estimate

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 approximately the respective modes

$$\begin{aligned} x_v^* &= Vp_v - (1 - p_v) \approx Vp_v \\ x_t^* &= Tp_t - (1 - p_t) \approx Tp_t \,, \end{aligned}$$

or

$$\begin{aligned} x_v^* &= (20)\,(0.015) = 0.3 \\ x_t^* &= (30)\,(0.1) = 3 \,. \end{aligned}$$

The convoluted mode $j^*$ ought to be the sum of the individual modes

$$j^* \approx x_v^* + x_t^* \,,$$

and using the numbers on hand, one finds

$$j^* \approx 3.3 \,.$$

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

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

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

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

$$D(0,3) = 0.2 \text{ gal/s}$$
$$D(1,2) = \left(0.44\overline{4} + 0.13\overline{3}\right) \text{ gal/s} = 0.57\overline{7} \text{ gal/s}$$
$$D(2,1) = \left(0.88\overline{8} + 0.066\overline{6}\right) \text{ gal/s} = 0.95\overline{5} \text{ gal/s}$$
$$D(3,0) = 1.3\overline{3} \text{ gal/s}$$

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.

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:

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

The total probability is the sum of convolutions 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 $x_v = 1$:

$$P_v(1) = \binom{20}{1} (1 - 0.015)^{19} (0.015)^1 \approx 0.2251$$
$$P_t(2) = \binom{30}{2} (1 - 0.1)^{28} (0.1)^2 \approx 0.2277$$
$$P_v(1) \cdot P_t(2) \approx 0.05126$$

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 $x_v = 3$:

$$P_v(3) = \binom{20}{3} (1 - 0.015)^{17} (0.015)^3 \approx 0.002976$$
$$P_t(0) = \binom{30}{0} (1 - 0.1)^{30} (0.1)^0 \approx 0.04239$$
$$P_v(3) \cdot P_t(0) \approx 0.0001262$$

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:

$$P(3) \approx 0.2394 \approx 23.94\%$$

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

$$\begin{aligned} P(1) &\approx 0.1044 + 0.009542 \\ &\approx 0.1139 \approx 11.39\% \,. \end{aligned}$$

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

$$\begin{aligned} P(4) = P_v(0) \cdot P_t(4) &+ P_v(1) \cdot P_t(3) \\ &+ P_v(2) \cdot P_t(2) + P_v(3) \cdot P_t(1) \\ &+ P_v(4) \cdot P_t(0) \,. \end{aligned}$$

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

$$\begin{aligned} P(4) = 0.1309 &+ 0.05315 \\ &+ 0.007416 + 0.0004205 \\ &+ .000008164 \,, \end{aligned}$$

or

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

To summarize, we found

$$\begin{aligned} P(0) &= 3.133\% \\ P(1) &= 11.39\% \\ P(2) &= 20.15\% \\ P(3) &= 23.94\% \\ P(4) &= 19.19\% \,, \end{aligned}$$

which is maximal at $j = 3$. Given that $P(4)$ begins a downward trend, we can be sure that all subsequent $P(j > 4)$ are all less than $P(3)$.

Summing each percentage above, we conclude that there is a 77.80% chance that any number from zero to four devices are in use simultaneously. This means there is a 22.20% chance that any number $5 \le j \le 50$ devices are in use simultaneously.

Reading the trend in the $P(j)$, we estimate that the probability should be less than 1% by say, $j = 10$, thus we define a variable

$$k = 10 \approx 3j^* \approx 1 + 9 \,,$$

which corresponds to one flush valve and nine flush tanks.

For a final flow rate we find

$$D(1, 9) = 1.04\bar{4} \, \frac{\text{gal}}{\text{s}} \,,$$

which is about 63 gallons per minute.

To reiterate the last step, one reasons that $P(k) = 1\%$ corresponds to the worst probable use case. The special value $k$ is also called a *design factor*. For this problem, there is about a 1% chance that more than 10 of the 50 fixtures are operating simultaneously.

### Deconvoluted 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.

To work toward something simpler, separately consider a (i) flush valve, (ii) flush tank, (iii) bathtub having the following characteristics[2]:

- 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

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

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

and finally for the bathtub:

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

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 $P(k_v, V) = 1\%$. The very same can be said for flush tanks by switching indices $v \to t$, $V \to T$, leading to

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

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

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

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

- $P_v(x_v, 25)$ equals 1% at $k_v = 3.671$
- $P_t(x_t, 25)$ equals 1% at $k_t = 0.4622$
- $P_b(x_b, 25)$ equals 1% at $k_b = 5.412$

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

$$D_v(k_v) = 3.671 \left(\frac{4\text{ gal}}{9\text{ s}}\right) = 97.89 \frac{\text{gal}}{\text{min}}$$
$$D_t(k_v) = 10.16 \left(\frac{4\text{ gal}}{60\text{ s}}\right) = 40.64 \frac{\text{gal}}{\text{min}}$$
$$D_b(k_b) = 5.412 \left(\frac{8\text{ gal}}{60\text{ s}}\right) = 43.30 \frac{\text{gal}}{\text{min}}$$

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

- $P_v(x_v, 50)$ equals 1% at $k_v = 5.194$
- $P_t(x_t, 50)$ equals 1% at $k_t = 16.72$
- $P_b(x_b, 50)$ equals 1% at $k_b = 8.139$

Then, for 50 fixtures:

$$D_v(k_v) = 5.194 \left(\frac{4\text{ gal}}{9\text{ s}}\right) = 138.5 \frac{\text{gal}}{\text{min}}$$
$$D_t(k_v) = 16.72 \left(\frac{4\text{ gal}}{60\text{ s}}\right) = 66.88 \frac{\text{gal}}{\text{min}}$$
$$D_b(k_b) = 8.139 \left(\frac{8\text{ gal}}{60\text{ s}}\right) = 65.11 \frac{\text{gal}}{\text{min}}$$

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

- $P_v(x_v, 75)$ equals 1% at $k_v = 6.509$
- $P_v(x_t, 75)$ equals 1% at $k_t = 22.84$
- $P_b(x_b, 75)$ equals 1% at $k_b = 10.58$

Then, for 75 fixtures:

$$D_v(k_v) = 6.509 \left(\frac{4\text{ gal}}{9\text{ s}}\right) = 173.6 \frac{\text{gal}}{\text{min}}$$
$$D_t(k_v) = 22.84 \left(\frac{4\text{ gal}}{60\text{ s}}\right) = 91.36 \frac{\text{gal}}{\text{min}}$$
$$D_b(k_b) = 10.58 \left(\frac{8\text{ gal}}{60\text{ s}}\right) = 84.64 \frac{\text{gal}}{\text{min}}$$

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

- $P_v(x_v, 100)$ equals 1% at $k_v = 7.720$
- $P_v(x_t, 100)$ equals 1% at $k_t = 28.74$
- $P_b(x_b, 100)$ equals 1% at $k_b = 12.87$

Then, for 100 fixtures:

$$D_v(k_v) = 7.720 \left(\frac{4\text{ gal}}{9\text{ s}}\right) = 205.9 \frac{\text{gal}}{\text{min}}$$
$$D_t(k_v) = 28.74 \left(\frac{4\text{ gal}}{60\text{ s}}\right) = 115.0 \frac{\text{gal}}{\text{min}}$$
$$D_b(k_b) = 12.87 \left(\frac{8\text{ gal}}{60\text{ s}}\right) = 103.0 \frac{\text{gal}}{\text{min}}$$

It would be more efficient to state the above results and all subsequent calculations in table form. In the following, the first column holds the number of fixtures, and the remaining three columns hold the gallons-per-minute (gpm) flow rates through the respective fixtures:

| **Fixture** (count) | **Valve** (gpm) | **Tank** (gpm) | **Bath** (gpm) |
|---|---|---|---|
| 5 | 51.65 | 15.25 | 20.15 |
| 10 | 66.29 | 22.58 | 27.20 |
| 15 | 78.06 | 29.00 | 33.08 |
| 20 | 88.41 | 34.97 | 38.37 |
| 25 | 97.89 | 40.64 | 43.30 |
| 50 | 138.5 | 68.88 | 65.11 |
| 75 | 173.6 | 91.36 | 84.64 |
| 100 | 205.9 | 114.9 | 103.0 |
| 125 | 236.4 | 138.0 | 120.5 |
| 150 | 265.8 | 160.6 | 137.6 |
| 175 | 294.2 | 183.0 | 154.4 |
| 200 | 322.0 | 205.1 | 170.8 |
| 250 | 375.8 | 248.8 | 202.9 |
| 300 | 428.0 | 292.1 | 234.4 |
| 350 | 489.0 | 334.9 | 265.4 |

### Fixture Units

One can construct a table similar to the above with a fixed gpm rate and a variable number of fixtures. Aiming for 50 gal/m, we find (i) $V = 5$ yields $D_v = 51.65\,\text{gal/m}$, (ii) $T = 34$ yields $D_t = 50.42\,\text{gal/m}$, (iii) $B = 33$ yields $D_v = 50.68\,\text{gal/m}$. Together, we jot the ratio 5 : 34 : 33 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 | 5 | 34 | 33 |
| 100 | 27 | 85 | 96 |
| 150 | 58 | 139 | 169 |
| 200 | 96 | 195 | 246 |
| 250 | 137 | 252 | 326 |
| 300 | 181 | 310 | 407 |

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. In ratio form, a subset of the above table reads:

| **Demand** (gpm) | **Valve** (ratio) | **Tank** (ratio) | **Bath** (ratio) |
|---|---|---|---|
| 150 | 1 | 2.397 | 2.914 |
| 200 | 1 | 2.031 | 2.563 |
| 250 | 1 | 1.839 | 2.380 |
| 300 | 1 | 1.713 | 2.249 |
| (Average:) | (1) | (1.995) | (2.523) |

Reading the average, observe that the water demand of one flush valve is like $\approx 2$ flush tanks, or like $\approx 2.5$ bathtubs. Stated in integer form, we have that ten flush valves is like five flush tanks, or like four bathtubs, implying the ratio

$$10 : 5 : 4\,.$$

The numbers 10, 5, 4 are the respective *fixture units*, abbreviated FU, for the flush valve, flush tank, and bathtub, respectively.

The fixture unit is born from comparing the likely use of flush valves, flush tanks, and bathtubs at a given flow rate such that the ratio of the respective fixture counts numerically rounds to a set of integers. Hunter didn't *need* to choose integers, all that matters is that the average fixture count ratio 1 : 2 : 2.5 is respected.

Generalizing the above, we may consider any water-conveying device, differentiating hot water demand, cold water demand, and drainage demand when applicable, as equivalent to some number $N/10$ flush valves. $N$ is measured in fixture units.

For a minimal example, we have that 10 fixture units corresponds to one flush valve, which to remind, conveys 4 gallons over an interval of 9 seconds of water per use, and is used once every 5 minutes. Note these numbers are decades old and have been refined since the 1940s.

The modern flush valve, according to CMR 10.00, is classified as *Toilet, Valve Operated*, assigned to have 6 fixture units. Accordingly, such a modern valve conveys $\approx 1.5$ gallons over 6 seconds. Thus we deduce that one fixture unit corresponds to 0.25 gallons conveyed over one second, or 15 gallons per minute. Up to a factor of $\approx 2$, we've essentially recovered the definition listed in CMR 10.00.

Note, finally, that the 1.25 inch diameter pipe never entered the analysis, and is essentially a red herring in the definition. This is for good reason, because we are meant to choose the pipe diameter *after* knowing the approximate flow rate through the pipe.

### 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** (gpm) | **Valve** (FU) | **Tank** (FU) | **Bath** (FU) |
|---|---|---|---|
| 150 | 580 | 695 | 676 |
| 200 | 960 | 975 | 984 |
| 250 | 1370 | 1260 | 1304 |
| 300 | 1810 | 1550 | 1628 |

Extending the table above and plotting the information on a graph, much as Hunter did, leads to Figure 24.1. 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 24.2. The result is called called *Hunter's Curve*.

**Demand vs Fixture Units**

Finally, we summarize the information in Hunter's curve using the tables that follow.

| **Demand (Load)** (FU) | **Valve** (gpm) | **Tank** (gpm) |
|---|---|---|
| 10 | 32.82 | 9.63 |
| 20 | 39.09 | 13.56 |
| 30 | 43.92 | 18.49* |
| 40 | 48.02 | 27.20 |
| 50 | 51.65 | 30.24 |
| 60 | 54.97 | 33.08 |
| 70 | 58.04 | 35.78 |
| 80 | 60.93 | 38.37 |
| 90 | 63.67 | 40.87 |

Before the asterisk we derive values from curve 2. At the asterisk we use the average of curves 2 and 3. After the asterisk we use curve 3 and throughout the next table.

| **Demand (Load)** (FU) | **Valve** (gpm) | **Tank** (gpm) |
|---|---|---|
| 100 | 66.29 | 43.30 |
| 140 | 75.84 | 52.45 |
| 180 | 84.40 | 61.00 |
| 200 | 88.41 | 65.11 |
| 250 | 97.89 | 75.05 |
| 300 | 106.8 | 84.60 |
| 400 | 123.2 | 102.9 |
| 500 | 138.5 | 120.5 |
| 750 | 173.6 | 162.6 |

After $\approx$ 1000 fixture units, all values are represented by curve 1.

| **Demand (Load)** (FU) | **Valve** (gpm) | **Tank** (gpm) |
|---|---|---|
| 1000 | 205.9 | 205.1 |
| 1250 | 236.4 | 236.4 |
| 1500 | 265.8 | 265.8 |
| 1750 | 294.2 | 294.2 |
| 2000 | 322.0 | 322.0 |
| 2500 | 375.8 | 375.8 |
| 3000 | 428.0 | 428.0 |
| 4000 | 529.0 | 529.0 |
| 5000 | 626.8 | 626.8 |

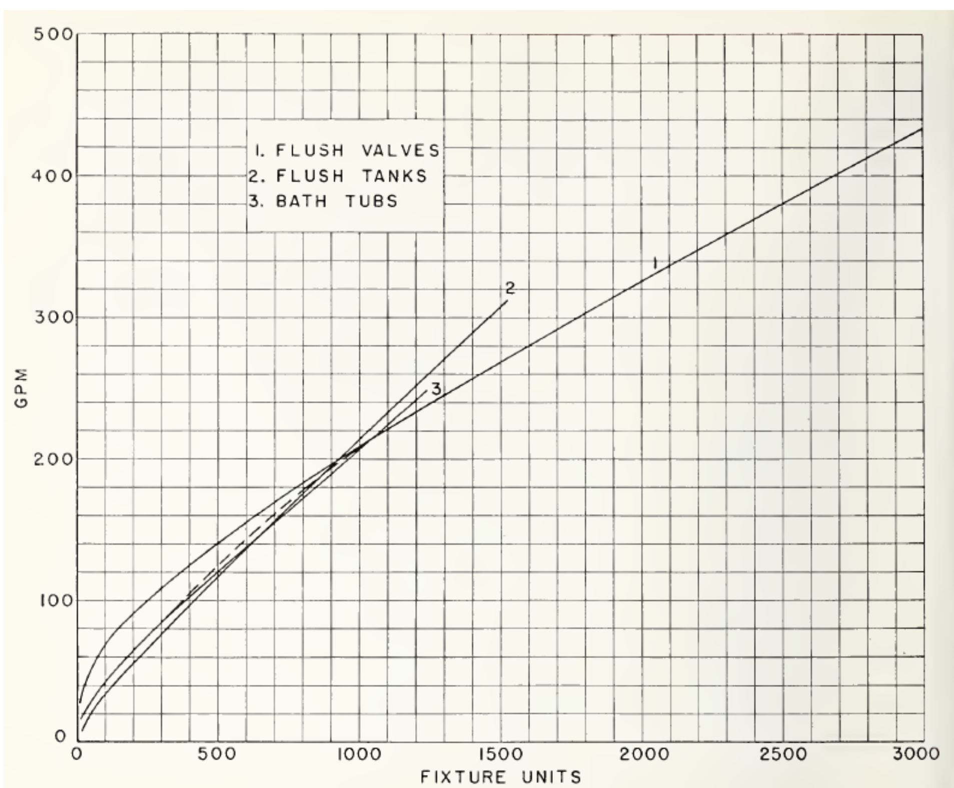


Figure 24.1: Gallons per minute versus fixture unit count for flush valves, flush tanks, and bathtubs. (*National Bureau of Standards Report: BMS 65*, 1940)

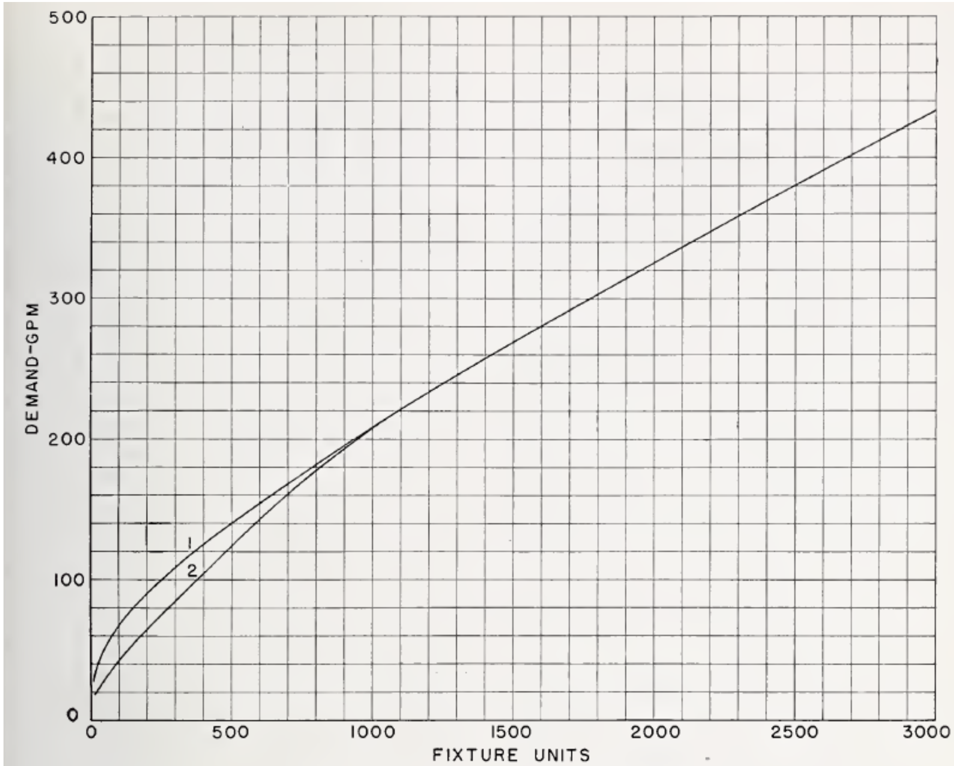


Figure 24.2: Hunter's Curve. (*National Bureau of Standards Report: BMS 65*, 1940)