A Comparison of British and American Plumbing Engineering Standards and Practices

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Terminology

Auxiliary vent stack	The vent piping running parallel to the sanitary stack for alleviating pressure differentials
Branch	A segment of piping
Discharge	Drainage flow from plumbing fixtures
DN	Diameter Nominal (measured in millimeters)
Fitting	A piping junction or elbow
Fixture drain	The segment of drainage piping between the fixture outlet and the adjoining drainage piping of another fixture
Foul drainage	Building drain, sanitary branch
Individual vent	A vent protecting only one trap
Sanitary appliances	Plumbing fixtures
Stack vent	Extension of the sanitary stack above the highest branch connection
Stack	Vertical drain or vent spanning one or more floors
Tap	Faucet
Washbasin	Lavatory
Wholesome water	Domestic water

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1.0 Introduction

Widespread adoption of sanitation technologies in the United Kingdom and United States in the 19th and early 20th century led to some of the first drafting of standards regarding the design and installation of plumbing systems. British and American plumbing methodologies have played an influential role in the development of plumbing standards and practices internationally, with many aspects developed in isolation, enabling contrasting comparisons to be made between the two systems. These comparisons may prove useful as plumbing design standards in both the US and UK face challenges revising traditional guidance to reflect modern building drainage system theory, water conservation measures, as well as other factors that impact the adaptability of plumbing systems to climate change mitigation measures. The specific comparisons made between national approaches are selective and focus on water supply and drainage systems while giving technical insight from past and present research. Key variations and similarities between the national and regional methodologies are featured to highlight how the discipline of plumbing engineering remains shaped by empirically derived practices from the last century.

1.1 Plumbing Engineering as a Profession

Plumbing engineering, generally known as public health engineering in the UK, is a specialized discipline of architectural engineering that encompasses building systems pertaining to water supply, sanitary drainage, storm drainage, fuel gases, medical gases, and occasionally fire protection. The term public health as it relates to water supply and drainage systems can be traced back to the early history of modern sanitation, most notably the Public Health Act of 1848 which aimed to provide water supply and drainage to buildings throughout England and Wales. The design of public health systems in the UK is predominantly independent from the mechanical engineering discipline, as is the case with plumbing systems in the US. This is not the case in some countries such as Canada, where the design of plumbing systems is generally fulfilled by mechanical engineers who also design heating, ventilation, and air conditioning systems. British public health engineers have professional representation through the Society of Public Health Engineers (SoPHE) under the Chartered Institute of Building Services Engineers (CIBSE), as well as the Chartered Institute of Plumbing and Heating Engineering (CIPHE). Both institutions publish engineering and design guidance as well as professional licensing. American plumbing engineers have representation under the American Society of Plumbing Engineers (ASPE), also publishing guidance and providing professional accreditation.

1.2 Standards

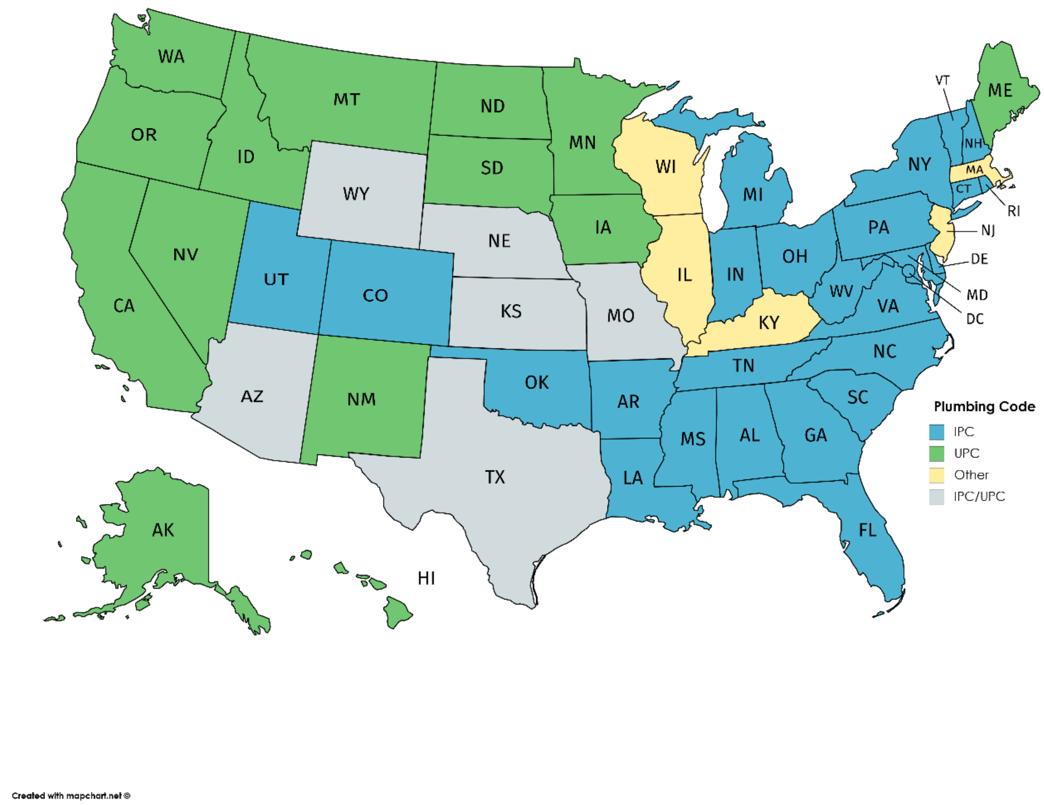
The UK uses various standards for the design and construction of plumbing systems drafted by British and European institutions. As a member of European Committee for Standardization (CEN), the UK shares a large portion of water supply and drainage standards with other European nations. These standards cover the production of sanitary appliances (plumbing fixtures), equipment, piping, and technical design criteria. While the mission of CEN is to support the economy of the European Union, membership extends to states outside of the EU and includes 34 European countries. This being the case, the recent withdrawal of the United Kingdom from the European Union will not affect CEN membership, meaning the application and participation in the development of European Standards will not change. The British Standards Institute (BSI) is the national standards body of the United Kingdom, operating under the Royal Charter. BSI is responsible for the development of national standards and the adoption of European Standards, publishing them as British Standards. The European Standards (European Norms), published in the UK under the prefix ‘BS EN’, are adopted without modifications, but often include national annexes as appendices. The harmonization process of plumbing standards in Europe faced significant challenges in terms of reaching consensus on various subjects and was nearly abandoned on several occasions [1, 2], however all parties persevered and the effort was largely considered successful. Base technical standards for systems such as water supply and drainage are used by all CEN countries. Additional requirements are drafted by the UK government in The Building Regulations and are published with additional guidance in Approved Documents. While these regulations are only required in England, similar requirements exist for the constituent countries of Wales, Scotland, and Northern Ireland.

Plumbing standards in the United States are generally adopted on a state-by-state basis. These standards are comprehensive documents, or 'codes', that provide baseline mandates related to the design and construction of plumbing systems and are most often written and published by non-governmental organizations. The International Plumbing Code [3] and Uniform Plumbing Code [4], published by the International Code Council (ICC) and the International Association of Plumbing and Mechanical Officials (IAPMO) respectively, are used predominantly across the US with a few remaining states using other codes. Each state serves as a market for ICC and IAPMO to advocate for the adoption of their model code publication, with many states making mostly minor modifications and relabeling publications as a local state plumbing codes. Attempts to harmonize the country under one plumbing code date back to the 1928 with the publishing of *BH13 Recommended Minimum Requirements for Plumbing* [5] by the National Bureau of Standards[1] (NBS) of the U.S. Department of Commerce. Preferences for locally drafted plumbing codes presented challenges to the acceptance of a national plumbing code, requiring a harmonization with several large codes in the publishing of the ASA A40.8 American Standard National Plumbing Code in 1955 [6]. This standard was drafted from the research of NBS while harmonizing other codes that had widespread adoption, with the intent on being accepted nationwide [7]. The ASA A40.8 harmonization project was eventually abandoned due to challenges meeting consensus during a revision of the publication, while attempts to create a national plumbing code continued under other standards organizations. Funding for the NBS plumbing program was terminated in the 1980s, slowing development of research supporting plumbing codes nationally [8, 9].

The Uniform Plumbing Code (UPC), originally published in 1945 under the development of plumbing inspectors, plumbers and engineers, was already established by the time the ASA A40.8 plumbing code was published. The UPC contains many of the NBS findings up until 1945, with some significant advancements following this date remaining unincorporated in the current edition. As the successor to the ASA A40.8 project, the National Standard Plumbing Code (NSPC) [10] was published by one of the sponsors of the original ASA A40.8 publication in 1971, gaining co-sponsorship from ASPE until 1980. State adoption of the NSPC receded and is now used by the state of New Jersey. Publishing rights to the NSPC were acquired by IAPMO in 2017. The International Plumbing Code (IPC), originally published in 1995 as the merger of three large regional codes, could also be considered a successor to the ASA A40.8, with large portions of the code today appearing identical to the 1955 edition. IAPMO and the ICC came together in 2005 with the goal of creating a single harmonized plumbing code, but this project was abandoned [11]. While efforts to harmonize the United States under one plumbing code have failed, most states have withdrawn locally developed codes and are now using either the IPC or UPC. In terms of population, 49% of the US live in IPC administered states, while 22% live in UPC administered states, with the remaining 28% living in states administering other codes or using both the IPC and UPC.

[1]Renamed to National Institute of Science and Technology (NIST)

Figure 1 – Plumbing code adoption by state



Regardless of nationality, occupations pertaining to plumbing often hold strong regional preferences toward specific plumbing methodologies. As prior efforts have demonstrated, the act of harmonizing plumbing standards, particularly in the area of sanitary drainage and venting, has often proved controversial or met with opposition. The universal caution expressed towards introducing new plumbing methods or modifying existing ones is not unwarranted considering system failures can result in serious consequences including injury or death from the expulsion of sanitary waste or sewer gases from plumbing fixtures, outbreaks in disease from domestic water systems, human contact with hazardous water temperatures, roof failure as a result of rainfall loads, and other incidents that compromise public health and safety. Alternative plumbing methodologies between regions often stem from a variance in safety factors that are challenging to assess, while others can be traced to empirical rules that attempt to balance simplicity, performance, and optimization of labor and resources. Many other approaches came about through research and testing of the mid-20th century, leading to inaccurate assumptions today as a result of evolving user behaviors and changes to the design of plumbing fixtures. Due to the empirically and regionally derived development of plumbing standards, comparisons can provide insight into unquestioned rules pertaining to specific regions and can provide technical justification for measures in some cases.

1.3 History of Sanitation in the United Kingdom

Prior to the late 16th century, sanitation in the UK was limited to the use of privies, also known as outhouses. Privies notably lack the means of transporting waste to another location and do not provide a protective water barrier between the user and soil waste. In 1596, John Harrington created what is considered the first flushing water closet, which was later installed in Richmond Palace for Queen Elizabeth I. This water closet featured a flushing cistern but lacked a water seal trap, allowing odor to ingress back through the fixture. Sanitation made little advancements until the Scottish watchmaker Alexander Cumming, widely regarded as the inventor of the modern water closet, filed a patent for his design in 1775, featuring a flushing mechanism and a water trap. In the years following, a number of English inventors, such as Joseph Bramah, improved on Cumming's design and successfully marketed the water closet throughout England [12]. The development of other sanitation technologies such as lavatories, baths, showers, and sinks followed.

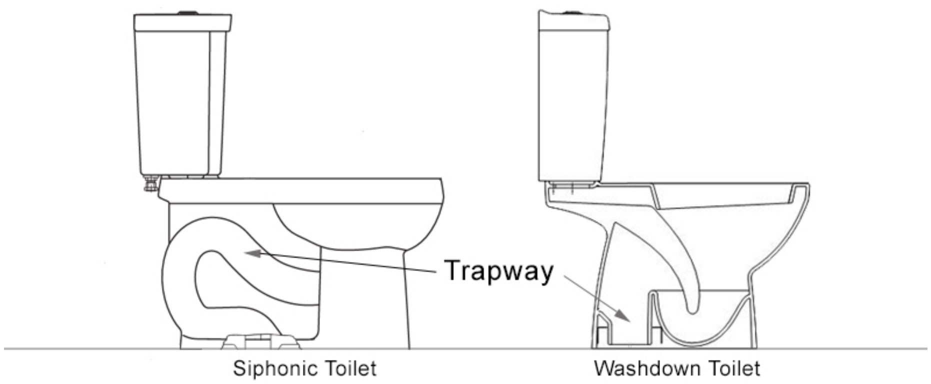
London experienced rapid growth throughout the industrial revolution, becoming the world's largest city by the early 1800s. Despite the growing adoption of water closets and other plumbing fixtures in wealthier households, poor sanitation conditions were commonplace, creating vulnerable conditions for the spread of disease. London experienced frequent outbreaks of cholera, resulting in the death of 14,137 people in 1849 [13]. Edwin Chadwick documented the poor sanitary conditions of working class populations and urged social reform towards increasing access to sanitation. Chadwick's efforts led to the Public Health Act of 1848, marking some of the first attempts to improve sanitation by the British government. The adoption of water closet technology had easily surpassed the development of drainage infrastructure. In 1851, half of the houses in London were estimated to be connected to sewers, with the remainder of plumbed houses discharging into private cesspools. These cesspools were often not emptied before overflowing and allowed sewage to seep through the earth, often contaminating groundwater [12]. The connection between cholera and contaminated drinking water was not well established until 1854, when the prominent epidemiologist John Snow identified the source of a major outbreak to a public handpump well, located 0.8 m (2.7 ft) from a leaking cesspool [14]. The second issuance of the Public Health Act was enacted in 1875 and required localities to ensure that every new house be constructed with sanitary appliances, along with water supply and sanitary drainage piping [15].

1.4 Sanitary Appliances

Water closets with flushing cisterns (flush tanks) are predominantly used throughout the UK, including commercial applications where flushometer valve water closets would normally be used in the US. Waste outlets on the back of water closets are most common, rather than through the floor. Flush tanks are often concealed in the wall with push-button flush controls above the water closet. Washdown type water closets are typical in the UK and the rest of Europe rather than the siphonic type common in the US. The washdown flush uses the gravitational force of the water from the tank to push the waste through the trapway, while a siphonic flush generates a siphon to pull the waste through the trapway. An immediately noticeable difference between these two types of water closets is the visible water surface area in the bowl is typically less in the washdown type than in the siphonic type. Washdown water closets are less prone to clogging due to the larger trapway. The American preference for large water surface area in the bowl of water closets has historically presented challenges matching the water efficiencies in Europe [16], though current siphon technology has comparable water efficiencies. Water closets are now commonly installed using 4.8 L (1.28 gal) per flush. The recent introduction of 3 L (0.8 gal) siphon water closets in the

US demonstrates further improvements to efficiencies. Similar to water closets, urinals typically use flushing cisterns in the UK. Flushing cisterns most often have no user control, and flush on a cycle dependent on the cistern filling time. To prevent flushing during low use periods, a solenoid valve is required upstream of the cistern supply and is actuated by a time-switch or occupancy sensor [17]. Direct user flushing control is also becoming a common alternative.

Figure 2 – Washdown and siphonic water closet comparison



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Shower and bath control valves typically feature rotational knobs on the left and right side of an exposed mixing valve to control the water flow and adjust the temperature. The single knob style with the concealed mixing valve, standard in the US, is also common in the UK. The pressures available at showers are often not high enough to support diagonal flow from fixed shower heads. As a result, diagonally fixed shower heads are less common in favor of detachable hand-showers or vertical flow shower heads.

Traditional British washbasins (lavatories) feature a separate faucet for hot and cold water. Until recent years, single faucets capable of supplying a mixed temperature, known as mixer taps, were required to have check valves on the fixture supply piping to prevent the cross-contamination of the hot and cold water systems. Current regulations have relaxed this requirement, under the condition that hot and cold water system pressures are equal [17].

Other fixtures such as bidets and squatting water closets, are more prevalent in the UK in comparison to the US, however they are less common than in other parts of Europe. Waste disposal units, installed at kitchen sinks, are not common in the UK but are permitted.

2.0 Sanitary Drainage

2.1 Peak Sanitary Drainage Loads

The method for calculating the predicted peak flow in European sanitary drainage systems uses an empirical power law formula and combines frequency-of-use and flow factors. The 'discharge unit' reflects the frequency of use and volume of the sanitary appliances. These values are shown in a table included in the EN 12056 standard. The empirical formula (Equation 1) was originally used in Germany and Switzerland prior to harmonization and is now used for selecting drainage loads throughout Europe [1].

Equation 1

$$Q_{ww} = K\sqrt{\Sigma DU}$$

Q_{ww} = Waste water flowrate (L/s)

K = Frequency factor (0.5 to 1.2 depending on congestion of occupancy type)

ΣDU = Sum of discharge units (System III values range between 0.3 for a washbasin and 1.3 for a kitchen sink)

Prior to the 1920s, sanitary drainage systems were often designed for the maximum possible flow from all fixtures. Recognizing the improbability of this occurring and the resulting costly oversizing of piping, Roy B. Hunter of the National Bureau of Standards in the US introduced a method using probability theory to estimate loadings in sanitary drainage systems, published in *BH2 Recommended Minimum Requirements for Plumbing in Dwellings and Similar Buildings* in 1923 [18]. This method used 'fixture units' to account for the drainage flow of a fixture and probability of simultaneous discharges with other fixtures. This approach spread to other plumbing codes throughout the US in the form of sizing tables. Conversions between drainage fixture units (DFU) and units of flow are not straightforward and differ between horizontal and vertical drains [19]. Hunter later revised drainage fixture units in his 1940 publication [20], allowing greater loads in drainage systems. Some of the supporting papers detailing the development of his drainage load estimations went missing, presenting challenges updating the method in later years [21]. The importance of reassessing the validity of drainage fixture units was identified by Hunter's successors at the NBS in 1964 [22], which remain mostly unchanged in both the IPC and UPC.

2.2 Horizontal Sanitary Drains

In 2001, countries throughout Europe withdrew national sanitary drainage standards and adopted the EN 12056 harmonized drainage standard. This publication was the work of a technical committee appointed by CEN with the aim of drafting a drainage standard that balances regional preferences with uniformity. Sanitary branch loading was one area where consensus was only achieved by separating drainage branch design into four separate systems. Sanitary branches in System I are designed to a peak flow filling 50% of the cross-sectional area of the drain, whereas Systems II and III are designed for a peak flow of 70% and 100% respectively. System III reflects the drainage theory developed in the United Kingdom, while System II reflects the practices used in Scandinavian countries and the Netherlands. Much of the rest of continental Europe uses System I, though System IV is used in France where graywater and soil drainage is piped separately [23, 24, 2]. The maximum branch loading and discharge unit values for appliances vary across all four systems. Many CEN countries require that one particular system be used to design the sanitary drainage whereas other countries, such as the United Kingdom, are more flexible [25]. For loadings in sanitary building drains, cross-sectional areas between 50% and 70% are recommended and are selected from tables or graphs calculated with the Colebrook-White equation featuring variable filling capacities and gradients. This is much more of a performance based approach in comparison to the prescriptive approach used in the US. American codes use a cross-sectional flow area of 50% for sanitary branches and building drains designed at peak flow. Drain diameters are selected using tables indicating the maximum drainage fixture units for a given gradient [19, 26]. To provide a simple comparison between the results of design methods used in the UK and US, maximum loadings have been calculated in Table 1, represented by the number of apartments serviced by sanitary drains of various diameters and gradients. The 70% flow area shows System III generally capable of carrying the drainage loads from more apartments when compared to the IPC and UPC, though when using a flow area of 50%, the allowable loading for System III is lower in most cases.

Table 1 - Maximum number of apartments on a sanitary drain

Diameter	Gradient	EN 12056 System III		IPC	UPC
		50% flow area	70% flow area		
DN 100 (4 in)	1%	5	14	20	15
	2%	10	28	24	19
DN 150 (6 in)	1%	48	133	77	52
	2%	96	270	93	65

Note: An apartment is assumed here to consist of a water closet, shower/bath, lavatory, sink, dishwashing machine, and clothes washer.

2.2.1 Gradients

British design guidance states that sanitary drainage velocities should fall between 0.75 m/s (2.5 ft/s) and 1.5 m/s (4.9 ft/s) to scour the pipe walls while keeping the solids in suspension. This minimum 'cleansing velocity' recommendation originated in the Victorian era in the UK [23, 27]. Loadings with recommended gradients are listed in Table 2.

Table 2 –Recommended minimum gradients for foul drains

Peak flow	Diameter	Minimum gradient	Maximum capacity
< 1 L/s (16 gpm)	DN 80 (3 in)	1:40 (2.5%)	4.1 L/s (65 gpm)
	DN 100 (4 in)	1:40 (2.5%)	9.2 L/s (146 gpm)
> 1 L/s (16 gpm)	DN 80 (3 in)	1:80 (1.3%)	2.8 L/s (44 gpm)
	DN 100 (4 in)	1:80[a] (1.3%)	6.3 L/s (100 gpm)
	DN 150 (6 in)	1:150[b] (0.7%)	15.0 L/s (238 gpm)

[a]Minimum of 1 WC
[b]Minimum of 5 WC
Source: Approved Document H [28]. Contains public sector information licensed under the Open Government Licence v3.0.

The loading and gradient selection tables in American codes are based on achieving a velocity of 0.6 m/s (2 ft/s) at 50% full [29, 30]. The velocity and cross-sectional flow area cannot be easily modified to suit a particular design condition since these are incorporated into the DFU table values. Common gradients for sanitary drainage in American codes range between 1% and 2%, with systems designed under the UPC typically favoring 2% and systems designed under the IPC tending to use shallower gradients of 1%. The concern of drainline transportation performance has grown in recent years in relation to the impacts of water conservation. Solid depositions in the sanitary drains have been studied by Heriot-Watt University in Edinburgh as well as the Plumbing Efficiency Research Coalition (PERC) in the US using physical and virtual testing methods. Both research efforts conclude that gradients of 1% for DN 80 (3 in) and DN 100 (4 in) drains offer lower performance when carrying the discharge of a water closet and recommend steeper gradients. DN 80 (3 in) drains were also generally found to perform better than DN 100 (4 in) drains, though only marginally under some conditions. In a Heriot-Watt study, the transportation distance was projected to be more than double in many cases with gradients increased from 1:100 (1%) to 1:60 (1.6%). The issue of solid deposition in drains with shallow gradients can often be remedied by configuring junctions from other sanitary branches in close proximity downstream of the water closet to increase the transportation distance [31, 32].

2.2.2 Sanitary Branches to Stacks

Individual appliance drains generally connect independently to stacks under System III, which is not typical under the other three European systems or American methods. Groups of identical appliance types, such as multiple water closets or multiple washbasins, are permitted to discharge into a common sanitary branch to enter the stack, but mixed appliance connections are less common. Junction fittings are frequently manufactured with side branch inlets to provide more flexibility for independent stack connections. Approved Document H and EN 12056-2 under System III require that some sanitary branches, depending on the appliances connecting to them, have a maximum limit between the appliance and the connection to the stack.

2.3 Sanitary Stack Types

2.3.1 Primary Ventilated Stacks

Significant advancements in the understanding of hydraulics and pneumatics in sanitary stacks were made in the 1950s and early 1960s through research and testing of the national laboratories of the Building Research Station (BRS) in the United Kingdom and the National Bureau of Standards in the United States. These public institutions developed the foundations of building drainage theory, providing Alfred Wise, a researcher with BRS, technical justification for the elimination of auxiliary vents for sanitary stacks and individual appliance ventilation. As discharges travel through a sanitary stack without separate vent piping, negative pressure builds after each branch discharge, which can be attenuated with a larger sanitary stack diameter. By calculating the maximum negative pressure in a stack, Wise found that drainage systems with ventilation only at the top of stacks were capable of serving up to 8 floors of appliances [33], and are often used today for stacks up to 20 floors [34, 35]. This configuration, originally known in the UK as the single stack vent[2], spread throughout Europe as a result of the proven performance and impact on labor and material, and was incorporated into EN 12056-2 as the 'primary ventilated stack'. While this method is used extensively in the rest of Europe and Asia, it remains uncommon in most of the US where the conventional stack with separate vent piping is typical. The theory for the single stack vent was originally proposed by architect J. Pickering Putnam at the American Institute of Architects convention in 1911, but lacked detailed design guidance [36]. The City of Philadelphia adopted this method shortly after and was later updated to include sizing based on drainage fixture units. The single stack vent was not included as an approved method[3] in either US model plumbing code until being introduced in the 2012 edition of the IPC [37, 34]. The Philadelphia single stack vent system is similar to the European primary ventilated stack, with a notable difference being that the loadings vary depending on the height of the stack. It is unclear if the researchers at BRS were aware of the single stack vent being used in Philadelphia during their initial testing and research work, suggesting that the British single stack was developed independently.

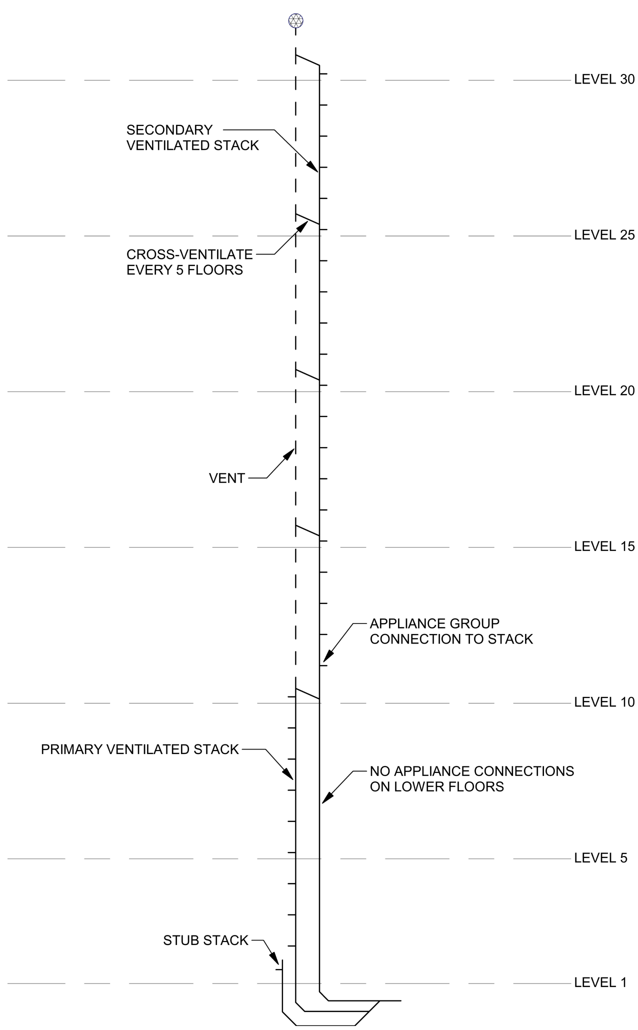
2.3.2 Secondary Ventilated Stacks

In cases where airflow in a primary ventilated stack configuration is unable to be attenuated within the differential pressure tolerances of the drainage system, such as in stacks of significant length or stacks receiving high discharge flows, additional means of conducting airflow will be necessary. Increasing the airflow can be accomplished by providing an auxiliary vent stack parallel to the sanitary stack with cross-connections between the stacks above the highest branch connection and below the lowest branch connection. Designated as the 'secondary ventilated stack' in EN 12056-2, this configuration is similar to

[2]Not to be confused with the Sovent single stack system, which uses stack aerator fittings to reduce the development of negative pressures
[3]Special permission may sometimes be granted from jurisdictions for the use of single stack vents or other methods not approved within a plumbing code, provided the engineer-of-record submits technical justification through an application process. The single stack system used in Philadelphia has been included in an appendix of the UPC since 2006 and appears identical to the single stack later incorporated in the IPC, but remains unlisted as an approved method.

the primary ventilated stack in that appliances may still connect to the stack without individual ventilation piping. Since relief connections are made between the sanitary stack and the ventilation stack, negative pressure development will be lessened as discharges enter the stack. While the tables provided in EN 12056-2 offer no guidance on stack height with respect to drainage loads, polling from SoPHE suggests that nearly half of public health engineers provide an auxiliary vent stack for sanitary stacks greater than 15 m (50 ft) or 20 m (66 ft) to reduce the magnitude of negative pressure developments [38]. Primary and secondary ventilated stacks are often used in conjunction for high-rise drainage designs. In this configuration (Figure 3), the secondary ventilated stack serves the upper floors of appliances, with a primary ventilated stack serving the lower floors. The stack vent from the primary ventilated stack serves as the auxiliary vent for the secondary ventilated stack, with the sanitary stack serving the upper floors bypassing the lower floors and running parallel to the primary ventilated stack.

Figure 3 – Primary and secondary ventilated stacks



The secondary vent stack configuration is also similar to a single stack vent system in the IPC, which requires an auxiliary vent stack to be provided for stacks serving more than 5 floors. This requirement is also typical for conventional stacks in the IPC. Assuming a floor-to-floor height in a multistory building of

3 m (10 ft), the IPC auxiliary vent stack requirement could be seen as comparable to the common British provision of an auxiliary vent stack for sanitary stacks greater than 15 m (50 ft) in height.

2.4 Maximum Sanitary Stack Capacities

Stack diameters in EN 12056-2 are selected based on the theoretical maximum discharge flow filling 1/6th of the annular cross-sectional area of the stack. This loading is consistent across all four systems in EN 12056-2. Stack sizing varied considerably across Europe prior to harmonization and consensus on loading methods was met by using the maximum cross-sectional area loading method developed by the National Bureau of Standards [1]. The work of Robert Wyly and Herbert Eaton at the NBS between 1952 [39] and 1961 [21] concluded that simultaneous discharges should be limited to between 1/3rd and 1/4th of the cross-sectional area of the stack. Wyly and Eaton state that as the flow area increases beyond 1/3rd, sheets of water break free from the annular form and disrupt airflow in the core of the stack, creating large pneumatic pressure fluctuations, noise, and vibration, compromising the water seals in fixture traps. These stack limits were observed earlier by Hunter in 1923 [18]. The conclusions of the NBS reports are reflected in the stack loading areas shown in the UPC and IPC as 1/4th, and 7/24th[4] respectively [19, 26]. Prior to European harmonization, a cross-sectional area of 1/4th was used in the UK under the CP 304 standard and the later BS 5572 standard. A cross-sectional area of 1/6th was selected by the CEN committee to provide a greater safety factor, but the values reflected in EN 12056-2 arbitrarily diverge from this loading, in some cases significantly, to satisfy the views of the group [16, 1]. Additionally, two categories of stack loadings are shown in EN 12056-2, with selections depending on the type of fitting used to connect the branch to the stack. Square entry stack connections, defined as junctions with an entry radius less than the drain diameter, have been historically standard in most of Europe whereas the United Kingdom has historically used swept stack entry connections, equivalent to the sanitary-tee used in the US. The stack loadings for square entries reflect the 1/6th cross-sectional loading whereas the swept connections are arbitrarily higher [16]. Swept connections limit disruption of the annular flow in the stack, as reported by Wyly and Eaton [21]. A comparison between maximum stack loadings for different methods can be seen in Table 3, calculating the number of standard apartment bathrooms permitted on various stack diameters. Notice that both the System III primary ventilated stack and the Philadelphia single stack vent limit loadings to around 40 bathrooms for DN 100 (4 in) stacks. The UPC stack is also limited to around 40 bathrooms, but is required to provide vent piping to fixtures prior to the stack connection. The empirical sizing recommendations of the Philadelphia single stack allow the same loading of the 23 m (75 ft) stack to be used for a stack up to 49 m (160 ft) if a larger diameter stack is used. Unlike the secondary ventilated stack, the Philadelphia single stack does not gain additional allowable drainage capacity with the provision of an auxiliary vent stack. The height limitations generally constrain the design of the Philadelphia single stack more than the loading, as can be seen for the 23 m (75 ft) limitation for DN 100 (4 in) stacks. Because the DN 125 (5 in) drain diameter is considered non-standard in the US, a DN 150 (6 in) sanitary stack with an auxiliary vent stack will usually be selected for apartment bathrooms in buildings that exceed 23 m (75 ft). DN 125 (5 in) stacks are non-standard in the UK as well but are increasingly being utilized in an effort to optimize drainage systems.

[4] 7/24th, being the mid-point between 1/4th and 1/3rd, was a specific loading tested in these reports

Table 3 – Number of apartment bathrooms permitted on a various stack diameters

Diameter	EN 12056 System III		IPC				UPC
	Primary Ventilated Stack	Secondary Ventilated Stack	Single Stack Vent			Conventional	
			<23 m (75 ft)	<49 m (160 ft)	>49 m (160 ft)		
DN 100 (4 in)	38	76	45	4	NA	100	43
DN 125 (5 in)	82	142	96	45	4	220	100
DN 150 (6 in)	219	478	203	96	45	380	230

Note: An apartment bathroom is assumed here to consist of a water closet, shower/bath, and lavatory.

2.5 Clearance of Blockages

Access for clearing blockages is required in BS EN 12056-2 every three floors on sanitary stacks for residential buildings and on every floor for commercial buildings [25]. The IPC and UPC do not require access to any part of stacks[5]. Inspection chambers are used for clearing blockages, with some sizes large enough for human entry. These chambers act as a hub for multiple building drain connections. Access fittings are similar to inspection chambers but are not generally large enough for human entry. Rodding eyes resemble floor cleanouts except with diagonal rather than vertical entry, and are a more recent introduction to the UK. Floor cleanouts and wall cleanouts are exclusively used in the US for clearing blockages in building drainage systems.

2.6 Ventilation

2.6.1 Ventilation of Sanitary Stacks

For all four systems shown in EN 12056-2, a vent from the stack should extend full size above the highest branch connection. This effectively serves as the vent for all appliances connecting into the stack. All British standards state that each vent from a stack is to be taken directly to atmosphere. It is however common practice to group a number of stacks together to minimize roof penetrations. The grouping of vents from stacks, known as vent headers in the IPC, is common in both American model codes. Vent header diameters in American codes are selected using the same table for sizing auxiliary vent stacks, with maximum lengths indicated alongside DFU loads, requiring larger vent diameters where maximum lengths cannot be met. The relationship of diameter and equivalent length[6] is missing from British and European design guidance on ventilation and stacks, possibly explaining aversions to combining stack vents into vent headers. Vent headers can impose additional airflow friction loss by extending the length to atmospheric termination, leading to greater negative pressures within the stack. Designs that do not compensate for these losses with larger diameter vent headers may experience failures of water seals in fixture traps. Dome cages, similar to those on roof drains, are required on vent terminations in the UK and impose a certain level of friction loss as the area is reduced. This requirement is not common in the US, and in practice, is often overlooked in UK installations.

[5] The requirement to place cleanouts at the base of every stack was removed in the 2012 edition of the IPC.
[6] Equivalent length translates fittings such as bends into a length of straight piping to simplify friction loss calculations.

A drainage airflow simulation program developed at Heriot-Watt University, known as AIRNET, allows drainage system designs to be analyzed to determine the location and magnitude of pressure differentials in the vent piping as well as airflow to water flow relationships. Comparisons to physical testing arrangements have shown AIRNET capable of reproducing test data. A simulated test using AIRNET at Heriot-Watt demonstrated that an arrangement of a secondary ventilated stack with unventilated fixture connections and an equal size vent from the stack was capable of reducing the magnitude of stack suction pressures when compared to a stack with individual vents to the fixtures without an auxiliary vent stack. The testing arrangement featured stacks serving 6 floors with one fixture per floor, and 4 of the 6 fixtures simultaneously discharging at 1 L/s (15.9 gpm). The sanitary stack diameter was DN 100 (4 in) with a DN 50 (2 in) vent stack from individual fixture vents (Figure 4a), which was compared to a DN 100 (4 in) auxiliary vent stack (Figure 4c), with both configurations venting the top of the stack. While this test exceeds actual peak flow conditions in a stack, it does demonstrate the comparative performance between these configurations. Because the UPC does not require an auxiliary vent for the sanitary stack unless it serves more than 10 floors, this general arrangement would be compliant. Additionally, both the IPC and UPC do not require vent connections at the top of stacks[7], presenting conditions where suction pressure is only exacerbated. It is however common in the US to provide a vent connection at the top of stacks in cases where auxiliary vents are also required. The pressure patterns in the conventional stack with individual DN 50 (2 in) vents (Figure 4a) matched the characteristics of the single stack (Figure 5), since the individual vent diameters were too small to relieve the suction pressures in the stack. When the same configuration was used for the conventional stack, except with DN 100 (4 in) individual fixture vents (Figure 4a), the suction at the base of the stack was reduced by a factor greater than 6. The stack arrangement with an auxiliary vent stack (Figure 4c) rather than individual fixture vents had nearly identical performance to the DN 100 (4 in) individual fixture vent arrangement (Figures 4b and 5). This scenario demonstrates the inability of individual vents to protect traps seals from induced siphonage and suggests that trap seals may be better maintained with a secondary ventilated stack than with a conventional stack. The conventional stack configuration used in these tests featured a stack vent above the highest branch connection, which is not required in the IPC or UPC. Alternatively, auxiliary vents are required for sanitary stacks serving more than 5 floors in the IPC and for sanitary stacks serving more than 10 floors in the UPC. Testing by John Swaffield, a researcher at Heriot-Watt, suggested that a vent from the stack of equal diameter or greater is necessary to relieve differential pressure fluctuations to maintain trap seals [34]. This recommendation has also been made by Alfred Steele of the American Society of Plumbing Engineers [26], though this is not required even for auxiliary vent stacks in many circumstances by the IPC and some circumstances in the UPC under certain loadings and stack lengths.

[7]The IPC requires vent connections at the top of stacks for special venting configurations, such as the single stack vent system or the waste stack vent.

Figure 4 – Sanitary stack configurations

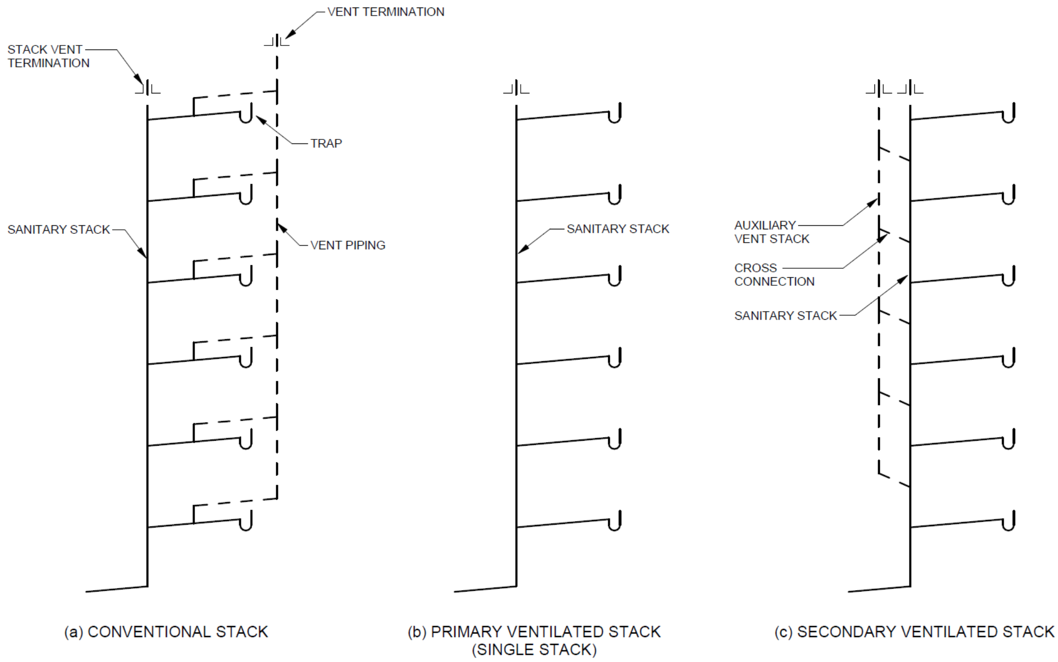


Figure 5 – Primary ventilated stack air pressure profile with multiple appliance discharges

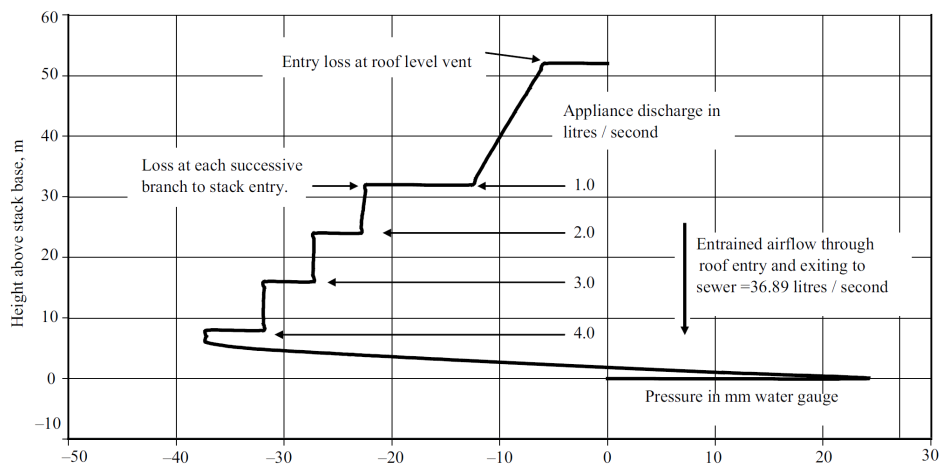


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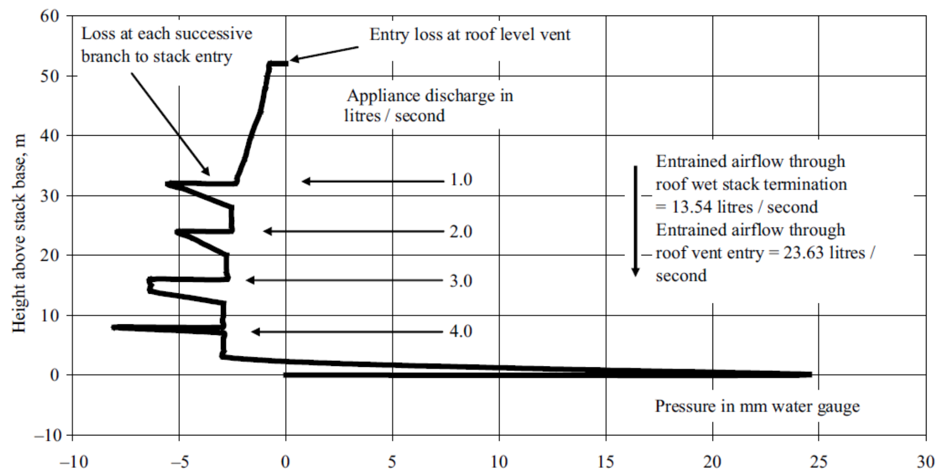
Figure 6 – Secondary ventilated stack air pressure profile with multiple appliance discharges



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The recommended diameter of the auxiliary vent stack for secondary ventilated discharge stacks is generally half that of the discharge stack in EN 12056-2, though this auxiliary vent converges into the vent from the top of the discharge stack, matching the diameter of the sanitary stack. National Annex D of BS EN 12056-2 recommends making cross-connections at every floor between the discharge and ventilation stacks. Polling suggests that only 25% of public health engineers cross-ventilate at every floor, with many cross-ventilating only every 3 to 5 floors or more [38]. As seen in Table 4, the IPC requires cross-ventilation every 10 floors while the UPC requires cross-ventilation every 5 floors.

Table 4 – Auxiliary vent stack requirements

Configuration requirements	EN 12056 System III	IPC	UPC
Auxiliary vent stack	Not required	Stacks > 5 floors	Stacks > 10 floors
Cross-ventilation	Not specified	Every 10 floors	Every 5 floors
Vent at top of stack	Yes, equal to sanitary stack	No[a]	No
Common ratio of diameters for vent and sanitary stacks	1/2 to 2/3	2/3 to 1/1	1/1
Vent piping for fixtures	No	Yes[a]	Yes

[a]Unless single stack vent or waste stack vent configuration is used.

As discharges fall in a stack, the water forms an annulus around the internal walls of the pipe, leaving the core mostly open for unrestricted airflow to relieve negative pressures. The developed friction from the discharges drags a column of air at the surface velocity of the water, a condition known as no-slip. This air velocity is communicated through a negative pressure wave and propagates at the speed of sound, roughly 340 m/s (1115 ft/s). Work from the NBS in 1961 [21] suggested a direct relationship between air and water in a sanitary stack, with the airflow not likely to exceed 1.5 times the terminal velocity of water in the stack. In the decades following, experiments at the BRS and Heriot-Watt [40, 34] proved the correlation between entrained airflow and annular flow area to be much more complex, contradicting the assumptions of NBS that form the basis of both American and European design standards today. Airflow in stacks is a factor of not only the flow volume, but also the quantity and location of discharges along the stack, and the length of the stack from the base to atmospheric termination. Rapid decelerations in flow occur when discharges enter the stack through branches, sending air pressure shockwaves throughout the drainage system. The magnitude of these shockwaves is highly dependent on the configuration of the system, making designing for relief challenging. Air is often entrained at 8 to 15 times the associated flow in the discharge stack, with the airflow to water flow ratio increasing with stack height and decreasing with flow volume [41, 34].

Experience and testing from public health engineers and researchers has shown the venting methods prescribed in EN 12056-2 to be insufficient for attenuating pressure differentials in discharge stacks of high-rise buildings. These shortcomings have led to induced siphonage and the expulsion of water seals from traps, particularly in stacks serving more than 30 floors with small diameter ventilation piping. Because airflow encounters frictional resistance as it travels through the vent piping toward the atmospheric termination point, a substantial length of piping may be unable to overcome the friction loss without subjecting the system to unacceptable pressures, leading to the failure of trap seals. Appropriate vent piping diameters are important for the same reason; a larger diameter vent will impose less airflow resistance in comparison to a smaller diameter vent. The only guidance offered in EN 12056-2 is that the ventilation pipes be "increased in size if they are long or have many bends" and then defers to national and local regulation for additional guidance. Some have suggested referring to American codes for stacks in high-rise buildings, while cautioning that these methods lead to oversizing [42, 41]. Swaffield suggested in *Transient Airflow in Building Drainage Systems* that

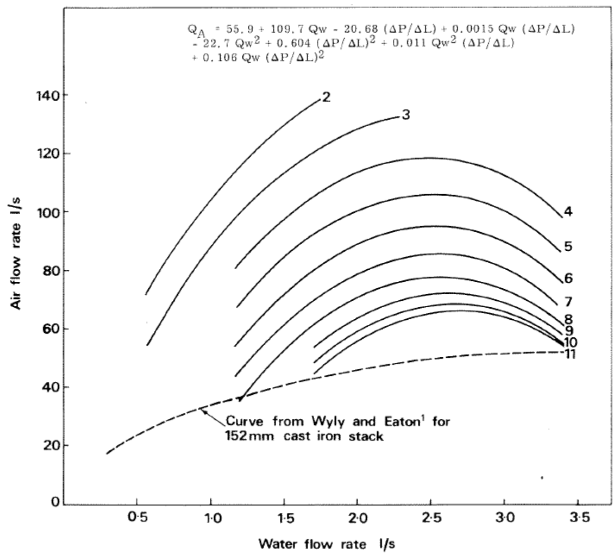
…setting a limit based on likely pressure excursions is a more refined approach as it recognises that the pressure level within a system depends upon the resistance to airflow provided by the design itself. Hence…there is no simple relationship between airflow and applied water downflow. Determining the maximum water flow must involve an iterative solution rather than a code 'look-up table'. Designs based on codes that tend to overdesign may not reveal this anomaly, however there is scope here to simplify code recommendations and to economise on system design and materials usage.

In application, an approach to stack ventilation design that directly addresses negative pressure would provide better performance than the recommendations in EN 12056-2 and a more optimized system than the approaches taken in American codes. This approach was taken by Lillywhite and Wise in 1969 [33] where suction pressures were limited within single stack systems to 375 N/m^2 or 38 mm (1.5 in) of water gauge, by either increasing the sanitary stack diameter or by providing an auxiliary vent stack. This method was incorporated into the design standard BS 5572, and remained in effect in the UK until European harmonization. Lillywhite and Wise understood that the relationship between air and water was not proportional as concluded by Wyly and Eaton, but assumed this to be true for the purposes of the report, citing ongoing research in this area. In 1973, B. J. Pink, a researcher with the British Research Establishment[8] (BRE), produced curves demonstrating the relationship between stack length, water flow, airflow, and suction pressures (Figure 7), resulting in airflow much higher than previously assumed in tall stacks [40]. These curves were empirically developed using a DN 150 (6 in) stack in an existing building, with discharges at varying flow rates and height. The theoretical basis of this relationship was later identified by Lynn Jack at Heriot-Watt University in the late 1990s, using a method which introduced a 'pseudo-friction factor' to translate the hydraulic forces within the stack to airflow. In 2000, the UK superseded the BS 5572 standard with the harmonized BS EN 12056 standard, therefore eliminating

[8]Renamed from the Building Research Station (BRS)

consideration of stack suction pressures in the design. This approach instead reverts back to the conclusions of Wyly and Eaton in 1961, where a simple airflow and water flow relationship is assumed. SoPHE is currently drafting a technical memorandum to provide additional design guidance on ventilation for stacks in high-rise buildings. This project aims to utilize current research on airflow in stacks while maintaining a somewhat simplified design approach.

Figure 7 – Air flow rate against water flow rate with pressure gradient ($N/m^2/m$) as parameter



1 $N/m^2/m$ = 0.0132 inches of water column per foot
Reproduced from *The effect of stack length on the air flow in drainage stacks* by B.J. Pink with permission from BRE

2.6.2 Active Ventilation

While providing networks of ventilation piping remains the most common method of alleviating pressure differentials within building drainage systems, active ventilation methods offer an alternative by addressing airflow with mechanical devices. The air admittance valve (AAV), invented in Sweden in the early 1970s, relieves negative pressures in the drainage system and is frequently used for venting sanitary appliances, branches, and occasionally stacks in the UK. The AAV is similar to a check valve in that it is designed to only allow airflow in one direction, preventing sewer gases from escaping into the building. Installations of AAVs are commonplace in the UK, particularly at lavatories and have been gaining acceptance in the US and are now permitted in most states. AAVs are known however to occasionally fail in the open position, releasing sewer gases into the occupant space. For the attenuation of positive pressures, a positive transient attenuator (PTA), more commonly known by the trademark acronym PAPA (positive airflow pressure attenuator), may be used to absorb airflow in the drainage system. These devices feature a bag secured within a cylindrical enclosure sealed in a vacuum that allows pressure to enter through the connection to the drainage system and expand the bag to absorb the pressure shockwaves. Researchers at Heriot-Watt introduced the concept and pioneered the development of the PTA, which were followed up with a number of studies demonstrating performance exceeding that of traditional piped ventilation, notably in taller high-rise buildings. The combination of AAV and PTA valves have also enabled the construction of drainage systems without any ventilation penetrations to the exterior [34].

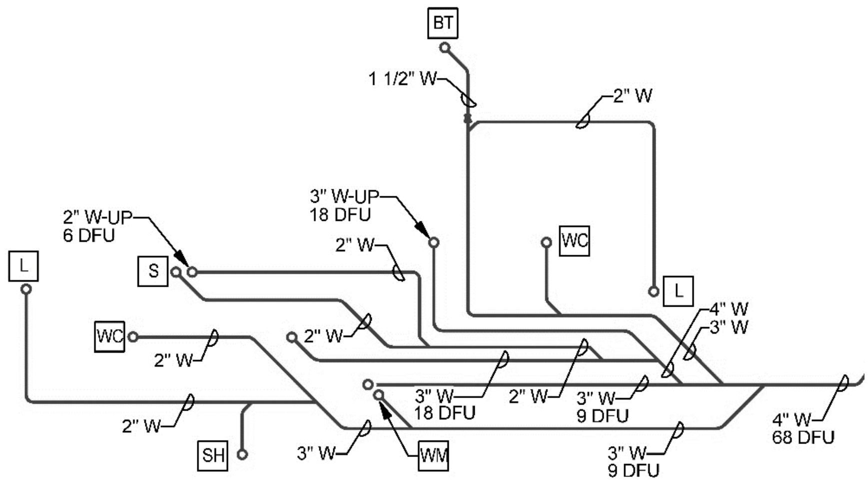
2.6.3 Restricted Stack Connections

The transition from negative pressure to positive pressure that occurs near the base of stacks can compromise nearby water seals in traps, prompting both British and American design recommendations to limit connections from adjoining sanitary branches. This pressure gradient characteristic is also present in stacks with auxiliary ventilation, but is much less pronounced, as shown in Figures 5 and 6. Positive pressures however are less affected by the presence of an auxiliary vent stack, necessitating special provisions to protect the water seals in traps near the stack base. National Annex D of BS EN 12056-2 states that for primary ventilated stacks serving up to 5 levels, branches must connect 750 mm (2.5 ft) above the stack base, while no connections from the lowest level can be made to the base of the stack for stacks greater than 5 levels. For low-rise single dwellings, connections at least 450 mm (1.5 ft) above the stack base are adequate. For stacks serving 20 levels or more, it is recommended that the lower 2 levels are served by a separate stack. CIBSE Guide G [27] advises against making branch connections within 2 m (6.5 ft) downstream from the stack, regardless of whether the stack has secondary ventilation.

Similar limitations are given for the Philadelphia single stack vent system for branch connections above the stack base, prohibiting connections to the lower 2 levels for stacks carrying discharges from 3 levels or more. For downstream connections, whether for single stacks or conventional stacks, the IPC prohibits any branch connections downstream of stacks within a length equivalent to at least 10 stack diameters. The basis for this limitation is the occurrence of a hydraulic jump, a phenomena that occurs as the flow velocity decreases below the wave speed in a horizontal drain, allowing a cresting wave to fill a greater area of the drain and potentially produce pneumatic effects as the area for airflow is reduced. This has been thought, particularly in the US, to commonly occur when water falling at terminal velocity enters the horizontal drain and begins a rapid deceleration in velocity. The frequency of this occurrence has been analyzed by researchers at Heriot-Watt, with difficulty producing a hydraulic jump during testing, except in very shallow drain gradients or in very rough piping. While the rapid deceleration downstream of a stack does increase the depth of the flow profile in the drain, wave attenuations tend to counteract this characteristic, limiting the likelihood of a hydraulic jump formation. Significant pressure fluctuations do occur near the base of stacks, though this is due to the airflow resistance imposed by the water curtain, causing pressure surges downstream. The water curtain forms as a result of the discharges breaking free from the annular flow profile at the transition into the horizontal drain. The hydraulic jump phenomena can often be observed at junctions where drainage flows converge, particularly at horizontal level entries [31].

The UPC generally does not restrict connections above or downstream of stacks, unless certain fixtures are present that tend to receive substantial amounts of soap suds. Soap suds decrease airflow potential by imposing additional friction losses in the piping, leading in some cases to the failure of trap seals and the introduction of soap through the trap and out of the fixture. Fixtures that the UPC considers to be suds producing include bathtubs, sinks, dishwashers, and washing machines. Where these fixtures discharge into a stack of 3 levels or more, no connections are permitted within 2.4 m (8 ft) above the stack base or downstream of the stack. Where the stack base is constrained near other horizontal drains, suds relief requirements are often met by providing additional fittings in the drainage configuration to increase the piping length until the distance is met, leading to a winding drain characteristic typical in UPC administered regions (Figure 8).

Figure 8 – Sanitary drainage conforming to suds relief requirements for an apartment building in California



2.6.4 Other Ventilation Methods

When a branch from an appliance or group of appliances cannot meet the requirements for unventilated branches in EN 12056-2, protection against siphonage can be fulfilled using a variety of methods, providing atmospheric relief to the appliance traps. The simplistic sizing recommendations for System III state that ventilation piping for any appliance trap or discharge branch can be as small as DN 25 (1 in) if less than 15 m (49 ft) in length or contains five bends or fewer. For ventilation piping that does not meet these requirements, the diameter is required to be at least DN 32 (1-1/4 in) [25].

A comparison against the three other European system types and American codes show the System III ventilation diameters to be exceptionally small. The small diameter vents are particularly interesting considering the large cross-sectional flow area for British sanitary branches. The UPC uses one set of table values for sizing all vent piping, while the IPC only provides table values for auxiliary vent stacks, directing other vents to be selected based on half of the diameter required for a sanitary drain of the equivalent loading. Both the IPC and UPC give direction to increase the diameter one pipe size if it exceeds specified lengths. Required diameters for vent piping at a given loading vary between the two codes but are generally larger in the UPC. Studies from the NBS [43] show that curved basin fixtures, such as lavatories, are the primary concern for self-siphonage, since most other fixture types have flat basins resulting in trailing discharges that tend to refill the trap following self-siphonage events.

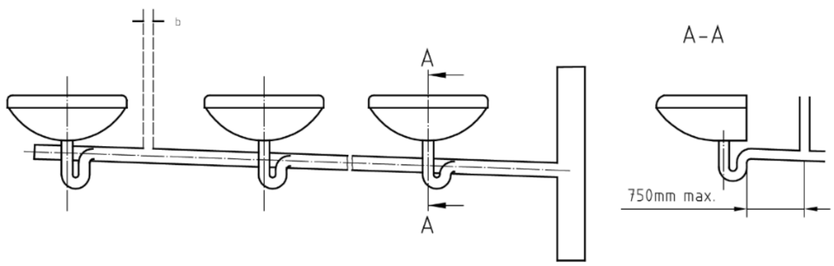
2.6.4.1 Individual Appliance Ventilation

Ventilating pipes that serve only one appliance trap are required to connect to the ventilation stack or terminate to atmosphere. Historically, individual ventilating pipes in the UK terminated outside through the wall adjacent to the appliance, providing pressure relief in close proximity to the trap. In instances where the routing of ventilation piping is challenging, an air admittance valve is often used at the appliance trap. Both the IPC and UPC allow configurations that utilize a remote vent connection from upstream drainage piping to eliminate the need for individual localized vents. Some of these configurations were more recently introduced to the UPC.

2.6.4.2 Branch Ventilation

Similar to circuit venting in American codes, ventilated discharge branches under System III may utilize a single ventilation pipe connection to provide siphonage protection for multiple appliances. The ventilation pipe connection is made between the two most upstream appliances (Figure 9).

Figure 9 – Boundary conditions for System III ventilated discharge branches



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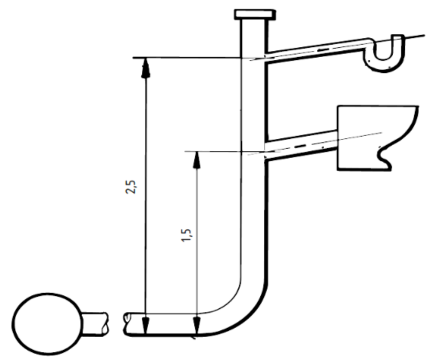
2.6.4.3 Combined Branches for Bath and Washbasins

One method included in National Annex D of BS EN 12056-2 enables the omission of an individual vent for the bath, provided that it horizontally joins the fixture drain of an individually vented washbasin, allowing a single connection into the stack. This is inherently similar to the horizontal wet vent configuration in American codes, where typically only the lavatory is vented and all other fixtures connect downstream of the fixture drain from the lavatory. Horizontal wet venting is often limited to fixtures in private bathrooms, such as a bathroom in a dwelling or hotel room, since these fixtures are less likely to experience congested use, and is one of the primary methods of optimizing the use of vent piping in multifamily buildings and hotels. While this configuration is permitted in both plumbing codes, horizontal wet venting is much less common in UPC administered regions, due to only being recently introduced in the 2009 edition.

2.6.4.4 Stub Stack

The stub stack is a unique British configuration that provides some simplicity to piping layouts, particularly on ground floors or at offsets in multistory buildings. Stub stacks are similar to primary ventilated stacks in that fixtures can discharge into the stack unventilated (Figure 10). The major difference between the two arrangements is that the top of the stub stack is capped rather than terminated to atmosphere. The height of stub stacks is limited to 2.5 m (8.2 ft) with a diameter of DN 100 (4 in) and a maximum discharge of 5 L/s (79 gpm). The horizontal drain receiving the stub stack must have a ventilated stack upstream or a dedicated vent that terminates to the atmosphere. Air admittance valves are optionally located at the top of the stub stack.

Figure 10 – Stub stack



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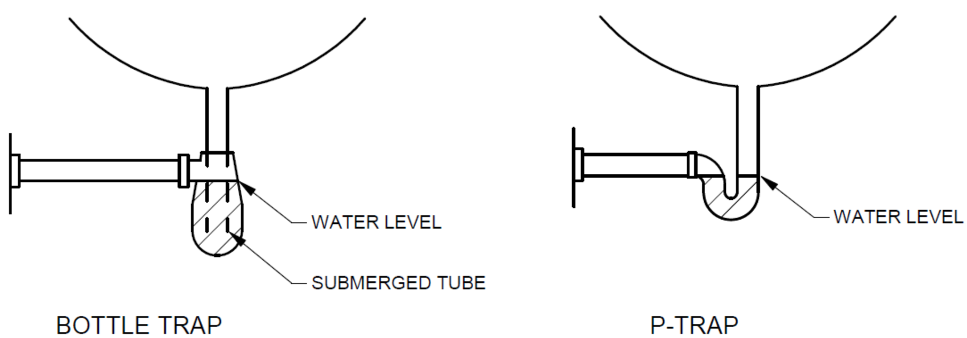
2.7 Traps for Sanitary Appliances

While the tubular P-trap is almost exclusively used for plumbing fixtures in the US, with exception of the water closet, a number of different trap types are used in the UK, some more effectively retaining trap seals during self-siphonage events. Washbasins, showers, and urinals typically use bottle traps which provide a higher level of protection against self-siphonage. Bottle traps have lower scouring performance than P-traps, leading to debris accumulation over time. For cleaning access, bottle traps feature an easily removable base. Other trap types utilize an integral AAV or use a resealable membrane rather than a water seal to prevent the ingress of gases.

Figure 11 – Comparison of bottle trap and P-trap



2.7.1 Water Seal Depth

Standardized water seal depths in traps varied across Europe prior to harmonization. The UK used a water seal of 75 mm (3 in), Switzerland used 70 mm (2.8 in) , Germany used between 60 mm and 50 mm (2.4 in and 2 in), while the rest of Europe used 50 mm (2 in). All traps are now required to have a minimum depth of 35 mm (1.4 in) after a peak discharge load, allowing evaporation of 10 mm (0.4 in) with a remainder of a 25 mm (1 in) seal. Traps must also be capable of an initial water seal depth of no less than 50 mm (2 in). These requirements are a compromise to a standardized water seal depth, allowing variation between CEN member countries while maintaining a uniform remaining seal depth [24]. Approved Document H and Annex D of BS EN 12056-2 require traps to have a water seal depth of 75 mm (3 in), with exceptions for water closets, floor drains, showers, and baths to have a seal of 50 mm (2 in). The requirement for

75 mm (3 in) water seals in washbasins along with the typical application of bottle traps support the 100% drain flow characteristics under System III, granting additional protection against water seal loss from self-siphonage. Similar to European requirements, American codes require traps with a 50 mm (2 in) water seal and must be capable of maintaining a minimum seal of 25 mm (1 in). Evaporation is typically only taken into consideration with floor drains or other similar fixtures subject to infrequent use and is addressed by providing water to the trap with an automatic trap filling device, such as a trap primer. The IPC allows a barrier type device to be installed as an alternative to a trap primer to limit evaporation.

2.7.2 Distance of Vent from Trap

In cases where the appliance drain is provided with an individual vent or connects to a ventilated branch, the maximum allowable distance between the trap and vent is 750 mm (2.5 ft) for System III. Similar limits are present in American plumbing codes, but vary depending on the size of the fixture drain and the gradient. Justification for a limit between the trap and vent can be found in Hunter's early work [18] and in BMS 126 [43], published in 1951 by John French and Herbert Eaton working with the NBS, attempting to identify likely conditions for self-siphonage. The NBS publications propose limits based on the drainage flow, slope, diameter, and whether a short or long radius swept junction fitting is used as the fixture drain transitions from horizontal to vertical at the vent connection. BMS 126 proposes a set of empirical equations, allowing a limit of 2.0 m (6.6 ft) for a DN 40 (1-1/2 in) drain and 1.5 m (4.9 ft) for a DN 32 (1-1/4 in) between the trap outlet and vent connection, for drains sloped at 2%. These trap to vent limitations are applicable to round basin fixtures with drainage flows exceeding 0.6 L/s (9 gpm), stating that trap to vent lengths may be greater for flat basin fixtures and practically unlimited at lower drainage flows and for water closets. While limited testing was undertaken for fixtures with flat basins such as bathtubs and sinks, French and Eaton concluded that self-siphonage was not a serious concern for these fixtures. American codes suggest that traps tend to self-siphon when the fall in gradient of the fixture drain exceeds the diameter of the fixture drain (Figure 12) or in some cases half the diameter. This simplistic relationship was proposed during the initial drafting of the UPC, and was later included in the ASA A40.8 code and IPC. For example, a DN 40 (1-1/2 in) drain has a maximum trap to vent distance of 1.8 m (6 ft) under the IPC, in comparison to a limit of 1.1 m (3.5 ft) under the UPC. The System III trap to vent limitation of 750 mm (2.5 ft) in EN 12056-2 does not however apply to unventilated sanitary branches that connect to primary or secondary ventilated stacks, even though the stack is essentially the vent for the trap. These maximum lengths do not take into consideration the gradient, with the exception of washbasins (Figures 13 and 14). The washbasin exception allows a length between the trap and ventilated stack of up to 1.75 m (5.7 ft) for DN 32 (1-1/4 in) drains sloped at 2%. For other appliances with unventilated drains connecting to primary ventilated stacks, the maximum allowable distance is significantly greater than the trap to vent distance and is dependent on the appliance type, generally between 1.7 m (5.6 ft) and 3.0 m (9.8 ft). Ventilated branches also have restrictions on the allowable distance between the trap and the stack, which may be intended to reduce the occurrence of blockages. These lengths are generally greater in comparison to unventilated branches.

Figure 12 – Trap to vent distance in IPC

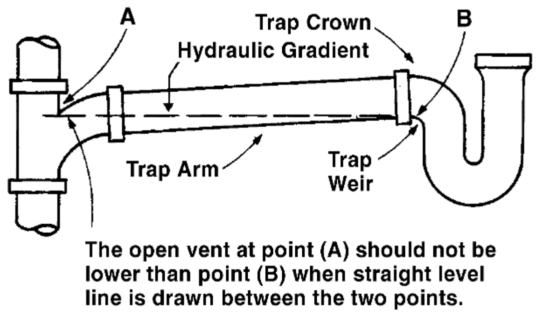
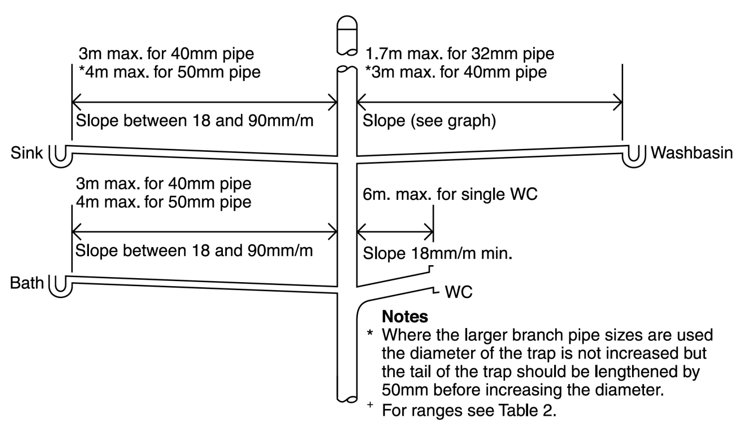


Table 5 - Trap and vent requirements

Requirement	British standards[a]	IPC	UPC
Minimum vent diameter	DN 25 (1 in)	DN 32 (1-1/4 in)	DN 32 (1-1/4 in)
Maximum distance between trap weir and individual vent	750 mm (30 in)	Diameter/Gradient[b]	Diameter/(2 x Gradient)[b]
Minimum distance between trap weir and individual vent	N/A	2 x Diameter	2 x Diameter

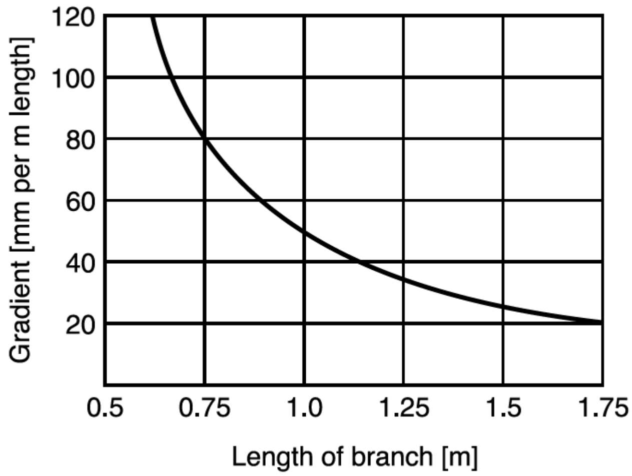
[a]Approved Document H, BS EN 12056-2
[b]The equation is used as the basis for rounded values for limits featured in the tables

Figure 13 – Trap to stack distances



1 m = 3.281 ft, 1 mm = 0.039 inches

Figure 14 – Maximum unvented branch length between trap and stack for washbasins - DN 32 (1-1/4 in)



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1 m = 3.281 ft, 1 mm = 0.039 inches

3 Domestic Water Systems

3.1 Peak Flow and Loading Units

Similar to the sizing of drainage systems, it was common until the mid-20th century for engineers to size domestic water piping based on the assumed flow of all downstream fixtures operating simultaneously. In an effort to optimize water supply piping, Roy Hunter revised his fixture unit method from 1924 and published the new method in the 1940 report *BMS 65 Methods of estimating loads in plumbing systems* [44]. This method uses a binomial distribution formula and statistical data collected from two hotels and an apartment building to estimate water closet loading at the 99th percentile peak flow. The water closet was assigned 10 fixture units, while various other plumbing fixtures were assigned lower values based on their volume and frequency of use in relation to the water closet loads. Hunter's probability method spread internationally, with a variation created in the UK by Henry Howick and published in 1965 in the CP 310 design standard. Similar to Hunter's fixture unit method, Howick used 'loading units' as weighted values for appliances to predict the peak flow. Following the publication of CP 310, Howick's method was included in the Institute of Plumbing[9] (IoP) design guide [23], evolving into an entirely separate sizing method with factors for high, medium, and low demand categories and modifications to the loading unit values. The CP 310 standard was replaced by BS 6700 and later by the current BS 8558 standard, remaining mostly unchanged from the original CP 310 publication [45, 46]. During the European harmonization of water supply standards, a peak flow probability method originally used in Switzerland was incorporated into EN 806-3 [47]. This method produced more accurate peak loading predictions compared to the two British methods, but is only permitted in the UK for the design of buildings consisting of single and multifamily dwellings [48]. For all other building types, current recommendations suggest the CIPHE method be used for sizing domestic water piping rather than the method featured in BS 8558 due to oversizing characteristics. Current research indicates that the EN 806-3 method still predicts flow rates well above peak demand for residences in the UK [47]. Sizing guidance for peak water demand is currently being investigated and revised under the LUNA (Loading Unit Normalisation Assessment) joint research

[9]Later renamed to the Chartered Institute of Plumbing and Heating Engineers (CIPHE)

project between CIPHE, CIBSE, SoPHE and Heriot-Watt University. This project aims to create a peak water demand method for residential applications in the UK using a partially stochastic probabilistic model [49]. Another study on non-domestic peak loading is also underway at Heriot-Watt [50]. A similar joint project between IAPMO, ASPE, and Aquacraft was recently completed in the US, introducing a new probabilistic method for water supply sizing using current data collected from water use patterns of plumbing fixtures (Figure 15) [51]. Under the Zero-Truncated Binomial Distribution method, also known as the Modified Wistort Method, peak water demand is calculated using statistical data collected from over 1000 single-family homes across the US to generate flow predictions for the 99th percentile peak demand. Fixture flowrates are also used in the calculation method to accommodate the reduced flow from water conserving fixtures. The design procedure proposed in this study is an approved method for jurisdictions adopting Appendix M of the 2018 UPC for single-family and multifamily buildings, while Hunter's curve will remain applicable to all other occupancy types. The IPC does not provide mandatory rules on the sizing of most water supply piping, allowing discretion to select a suitable method for the application. Table 6 gives a comparison of the number of apartments serviceable by a DN 50 (2 in) domestic water pipe using each of the design methods.

Figure 15 – Average hourly volume of water use at a fixture per home per day in the United States

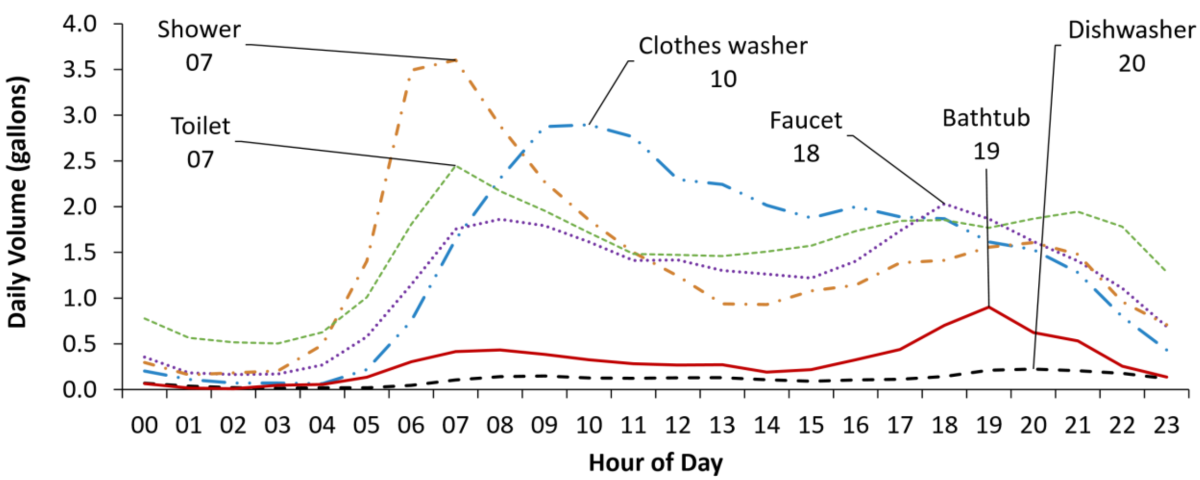

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Table 6 – Maximum number of apartments on DN 50 (2 in) domestic water service

Design Method	EN 806-3	UPC Appendix M Modified Wistort Method	IPC Appendix E Hunter's Curve	UPC Appendix A Hunter's Curve
Fixture/Loading Units per Apartment	12 LU	N/A	7.8 WSFU	14.5 WSFU
Velocity	2.0 m/s (6.6 ft/s)	2.4 m/s (8 ft/s)	2.4 m/s (8 ft/s)	2.4 m/s (8 ft/s)
Internal Diameter	52 mm (2.05 in)	50 mm (1.99 in)	50 mm (1.99 in)	50 mm (1.99 in)
Apartments	116	79	33	20

Note: An apartment is assumed here to consist of a water closet, lavatory, bath/shower, sink, washing machine, and dishwasher. For Modified Wistort Method, 1.9 L/min (0.5 gpm) is assumed here for the lavatory faucet and 5.7 L/min (1.5 gpm) is assumed for the kitchen sink.

3.2 Domestic Water Pressure

British water suppliers aim to deliver a minimum of 1 bar (14.5 psi) to buildings [23]. While EN 806-3 requires the minimum pressure at sanitary appliances to be a minimum of 1 bar (14.5 psi), this is not possible in many instances in the UK. High pressure appliances are designated as Type 1 in Approved Document G [52] and can operate with a minimum pressure of 0.5 bar (7.3 psi) at faucets and 0.3 bar (4.4 psi) at showers, while low pressure appliances are designated as Type 2 with a minimum pressure of 0.1 bar (1.5 psi) for faucets and showers. Protection against pressure is required above 5 bar (72 psi) at sanitary appliances. Lower pressure municipal systems tend to have higher risks of backflow and issues of water service dependability. In the US, the IPC requires minimum pressures ranging between 0.6 bar (8 psi) to 1.4 bar (20 psi) for most plumbing fixtures, and 2.4 bar (35 psi) for flushometer valve water closets, whereas the UPC requires a minimum pressure of 0.6 bar (8 psi) at all fixtures except flushometer valve water closets where at least 1 bar (15 psi) is required. Municipal water in the US is typically available at pressures between 2.8 bar (40 psi) and 4.1 bar (70 psi).

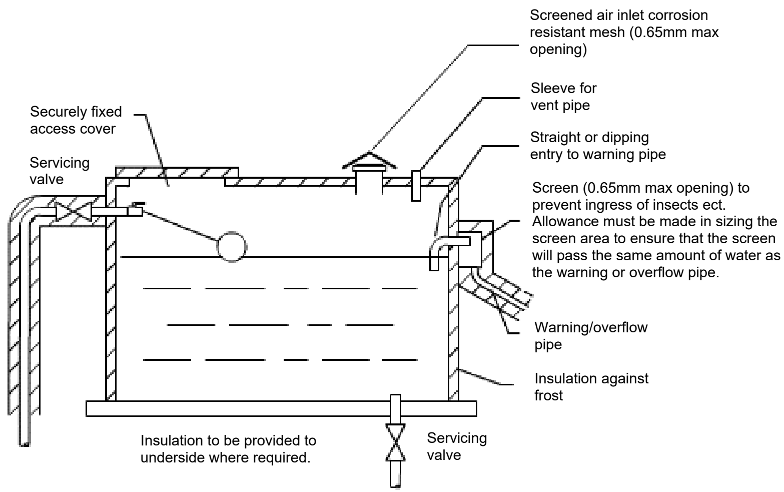
3.3 Velocities

EN 806-3 limits the maximum flow velocity to 2.0 m/s (6.6 ft/s) for domestic water piping, but allowances are given for velocities to individual appliances to reach up 4.0 m/s (13.1 ft/s) [53]. For most occupancies, CIPHE design guidance recommends not exceeding 1.5 m/s (5 ft/s) for acoustic reasons [23]. Flow velocities in the US are generally designed to a maximum of 2.4 m/s (8 ft/s) for cold water and 1.5 m/s (5 ft/s) for hot water. The temperature based velocity recommendations are an attempt to address the increased erosion properties of higher temperature water. These maximum velocities are mandatory in the UPC while the IPC defers velocities and other design components such as peak flow calculations to accepted engineering practice, while providing noncompulsory guidance in an appendix.

3.4 Cold Water Storage

To provide backflow protection and mitigate issues concerning reliability and variable pressures, a water storage cistern with an air gap is often required by British water suppliers for commercial, industrial, and multifamily buildings. The requirement for water storage is uncommon in the US and the rest of Europe, though cities such as New York City, Houston, and San Jose require domestic water storage or break tanks for certain building types, particularly when booster pumps are required. Backflow protection is most often provided by a backflow preventer valve at domestic water service entrances to buildings in the US. In the UK, the domestic water service typically terminates to the cistern with an airgap and provides water to the rest of the building by either gravity in the case of an elevated tank or by a booster pump. The water service reliability issues are due to variable water pressures, tending to decrease during high-use periods as a result of network friction losses and increase during low use periods. Cisterns are recommended to be cleaned a minimum of once per year to prevent sediment buildup leading to bacterial growth or other water quality issues. The recommended turnover of domestic water in storage varies depending on occupancy type, but is recommended not to exceed 24 hours [23]. Appliances that provide drinking water, referred to as ‘wholesome water’ in the Building Regulations, are sometimes located upstream of the storage tank, to maintain water quality.

Figure 16 – Requirements for domestic water storage cisterns



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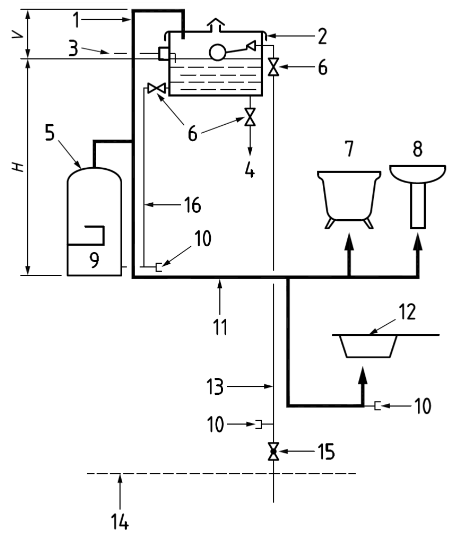
3.5 Domestic Hot Water Systems

British multifamily buildings such as apartments and condos typically do not use central water heating systems, as is typical in the US. Most multifamily buildings in the UK feature an individual water heating source. Domestic hot water is usually generated with a gas or electric water heater or a specialized heat exchanger known as a Heat Interface Unit (HIU), which transfers heat from a central hydronic loop to provide instantaneous domestic hot water. An HIU is a heat exchanger packaged in a small enclosure, with a balancing valve or pump, small thermal expansion tank and other components. This allows a non-potable source to provide domestic hot water on-demand to the appliances. It is also common for domestic hot water storage tanks to be heated with hydronic heat sources by means of a heat exchanger.

For domestic water systems fed from storage cisterns, the hot water system will generally be configured in what is classified as a vented system. The vented hot water cylinder is fed from a cold water cistern and provided with a relief pipe to discharge back into the storage cistern in cases of over-pressurization (Figure 18). This allows for the expansion of water without relying on expansion tanks or mechanical valves to accommodate excessive pressures. Unvented hot water cylinders over 15 L (4 gal) in storage volume were prohibited under the Model Water Bylaws until 1986 due to safety concerns [54]. Vented systems are not typical in larger new construction, as gravity fed domestic water systems are becoming less commonplace. Temperature and pressure relief valves are required to discharge when temperatures exceed 95°C (203°F) and when pressures are in excess of 50 kPa (7 psi) to 150 kPa (22 psi) above maximum working pressure [48]. In the US, the IPC requires a maximum temperature of 99°C (210°F) with pressures not exceeding 1035 kPa (150 psi). The UPC defers to manufacturers for maximum temperature and pressure requirements.

Figure 17 – Schematic example of a direct (vented) hot water system with cistern



$V \leq (H \times 0.04) + 0.15$

Key

1	Vent pipe	9	Heat source, e.g. immersion heater
2	Cold water storage cistern	10	Draining valve
3	Warning pipe	11	Hot water distributing pipes
4	Cold water distributing pipe	12	Kitchen sink
5	Direct (vented) hot water storage vessel	13	Supply pipe
6	Servicing valve	14	Floor level
7	Bath	15	Stopvalve
8	Wash basin	16	Cold feed pipe

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3.6 Legionella Growth Mitigation

3.6.1 History

In 1973, a Spanish hotel popular with British tourists, Rio Park Hotel, encountered an unidentified bacterial outbreak, infecting 89 hotel guests with a respiratory infection similar to pneumonia. Another outbreak was identified in the US three years later with similar symptoms at an American Legion convention in a Philadelphia hotel, infecting 182 people, with the condition becoming known as Legionnaires disease. This outbreak gained global attention as microbiologists with the Centers for Disease Control searched for the source. Months later, legionella pneumophila bacteria was discovered in a cooling tower on the roof and identified as the outbreak source, which had likely spread from the cooling tower into the windows of guests. During the same year, an outbreak occurred again at the Spanish Rio Park Hotel and was traced back to legionella in the domestic hot water system at the showers. After disinfection of the domestic hot water system, the temperature throughout the system was maintained between 50°C and 60°C and ended further cases of Legionnaire's disease at the hotel. Overall, 150 British tourists were infected, leading to the fatalities of 4 people [55, 56]. The first documented outbreak occurred in the UK two years later in 1979 and was traced to the domestic water system [57]. After three additional outbreaks in the UK over the following years, a 1985 outbreak sourced from a cooling tower at the Stafford District Hospital infected 68 people and was identified as the second largest globally at the time, prompting efforts to implement control measures for building water systems [58].

3.6.2 Standards and Technical Guidance

In 1987, CIBSE published one of the first comprehensive design guides on the mitigation of legionella growth in building water systems [59]. The Health and Safety Executive (HSE), a UK government agency, released the Approved Code of Practice L8 in 1991, creating framework for responsibility and direction to implement specific mitigation measures. Technical direction on mitigation strategies is currently provided in HSG 274 Part 2 [60] along with updated guidance in TM13 from CIBSE.

In the US, the implementation of legionella mitigation measures for domestic water systems is limited, particularly for buildings other than healthcare facilities. The 2018 editions of the IPC and UPC do not require consideration to be given for mitigating legionella growth in domestic water systems, though the 2021 edition of the UPC will require mitigation measures to be implemented, such as those published by ASHRAE. Guidelines from ASHRAE are used on a voluntary basis by engineers, but are not compulsory, leaving many to overlook the issue of legionella growth in domestic water systems entirely. ASHRAE 188 addresses the risks imposed by legionella growth in domestic water systems and specifies the duties of responsible parties, including building owners and design engineers. This standard is written with the intent of being adopted by jurisdictions or plumbing codes for enforcement. For technical recommendations, such as minimum circulation temperatures and disinfection methods, ASHRAE 188 redirects to ASHRAE Guideline 12 [61].

3.6.3 Legionnaires' Disease Statistics

The CDC reported 7458 cases (2.29 cases/100 000 people) of Legionnaires' disease in the US for 2017 whereas the ECDC reported 504 (0.75 cases/100 000 people) in the UK [62, 63]. Public Health England reported that nearly 50% of cases in 2017 were connected with traveling abroad, demonstrating the regional disparity of Legionnaires' disease infections. While infection rates fluctuate each year, the UK maintains one of the lowest rates of Legionnaires' disease in Europe, with the EU averaging in 2017 an infection rate of 1.69 cases/100 000 people, more than double that of the UK, with a total of 8731 cases. The US and Europe have seen an increase in Legionnaires' disease cases, with the US rate increasing considerably in recent years. It is widely accepted that cases of Legionnaires' disease are underreported, with one study suggesting that between 52 000 and 70 000 cases of Legionnaires' disease are likely occurring in the US annually [64]. While there remain uncertainties in comparing infection rates between any two countries due to inconsistencies, such as differences in reporting, this does not dismiss infection rate disparities or the impact of mitigation strategies on a national scale.

3.6.4 Temperature Control and Thermal Injury

The Health and Safety Executive limits the minimum temperature in domestic hot water systems to 50°C (122°F)[10] in HSG 274-2, slightly higher than the temperature shown in the 2020 edition of ASHRAE Guideline 12 of 49°C (120°F). This minimum temperature must be reached within 60 seconds of drawing water from a fixture or within a distance equivalent to 0.5 L (0.125 gal) of internal piping volume from the circulation piping, though Water Regulations guidance recommends limiting the delivery time further to 30 seconds [48, 17]. This deviates from the European EN 806-2 domestic water standard [65], where a temperature of 60°C (140°F) must be reached within 30 seconds after drawing hot water from an appliance, but gives exceptions to local or national regulations to provide alternative values. The alternative approach in the UK results in considerable reductions to energy loss through the piping. For appliances without scald protection, thermal injury risks at taps are significantly reduced with lower hot

[10] 55°C (131°F) for healthcare occupancies

water distribution temperatures. A temperature of 60°C (140°F) will produce a first degree burn within 2 seconds whereas a temperature of 50°C (122°F) will produce a first degree burn in 60 seconds [66]. British guidance directs storage water heaters to be set at a minimum of 60°C (140°F) [60, 48]. Domestic hot water is generally distributed throughout the piping system at the temperature leaving the water heating source with scald protection valves only at specific appliances. HSG 274-2 requires cold water temperatures to drop below 20°C (68°F) within 120 seconds of drawing water from appliances and cold water cisterns to be kept below 20°C (68°F), except for vented hot water systems where a maximum of 25°C (77°F) is acceptable when receiving the temperature and pressure relief from water heaters [17].

In the US, a master thermostatic mixing valve is typically provided to reduce the hot water distribution temperature after leaving the water heating source, where water is usually stored at 60°C (140°F). In addition to the master mixing valve, scald protection valves are also provided at specific fixtures. Traditionally, the distribution temperature at the master mixing valve is reduced to either 49°C (120°F) or 43°C (110°F) after leaving the water heater for distribution, with the circulated return temperature arriving back at the heat source at around 46°C (115°F) or 41°C (105°F). Operating domestic hot water systems at these temperatures has come under increased scrutiny in recent years as risks and liabilities of Legionnaires' disease have gained recognition in the US. Controlling distribution temperatures within 3°C (5°F) above the minimum return temperature has been suggested to balance considerations of thermal injury, heat loss, and legionella growth mitigation. Distribution at 52°C (125°F) reduces thermal energy losses by more than 20% in most applications when compared to 60°C (140°F) and reduces thermal injury risk by increasing the exposure time required to produce first degree burns by a factor of 2.5, and second degree burns by a factor of 5 [66].

The Department of Health and Social Care, a governmental department for England, issues specific maximum temperature limitations for appliances in healthcare facilities. Most other occupancies or appliances have no requirements for scald prevention valves, with the exception of baths, which are limited to a temperature of 48°C (118°F) and 43°C (110°F) for appliances in public buildings [52, 67]. The IPC and UPC require showers and bathtubs to be limited to 49°C (120°F) and bidets to be limited to 43°C (110°F). Public lavatories are limited in the IPC to 43°C (110°F) and 49°C (120°F) in the UPC.

4.0 Decarbonization of water heating and the phaseout of natural gas

On June 27th 2019, the UK became the first major global economy to require net zero greenhouse gas[11] (GHG) emissions by 2050 [68]. This legislation came following the Paris Agreement, signed as part of the United Nations Framework Convention on Climate Change in 2015, serving as a non-binding commitment to limit global warming to 2°C above pre-industrial levels by 2050 and pursue efforts to limit warming to 1.5°C [69]. The Committee on Climate Change (CCC), an independent body appointed by the UK parliament, is responsible for advising the government on policies to meet national climate commitments.

Heating is mostly provided in the UK through the combustion of natural gas and stands as the largest source of GHG emissions in the UK [70]. Phasing out the installation of natural gas in new buildings is considered a key first step for decarbonization, which is currently used in many buildings for space heating, water heating, and cooking. Natural gas makes up over 80% of the fuel share in the UK, more

[11]Greenhouse gases such as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, as defined by the Kyoto protocol

than the natural gas fuel share of 50% in the US and more than most other European countries [70]. Natural gas is a non-renewable fossil fuel primarily composed of methane, a highly potent greenhouse gas with a global warming potential[12] 86 times greater than carbon dioxide [71]. Natural gas contributes to greenhouse gases in the atmosphere through combustion in the form of carbon dioxide as well as through gas leakage during the production and transportation of gases to the point of use. In some cases, a natural gas leakage rate of 3.2% or greater has been found to result in greater GHG emissions in comparison to other fossil fuel energy sources such as coal [72]. The leakage of methane from production to the point of delivery in the US has been estimated to be between 3.6% and 7.9% for shale gas and 1.7% and 6.0% for conventional gas [73]. To achieve net zero emissions by 2050, the CCC recommends against the installation of fossil fuel dependent energy sources in new construction, such as natural gas. Following this phase, existing buildings will need to be retrofitted to meet the 2050 emissions target [74]. An update to Part L of the Building Regulations is set to prohibit fossil fuel heat sources from being installed in new residential buildings beginning in 2025 [75].

One of the primary pathways for decarbonizing buildings under implementation internationally is the electrification of all building services. Under this strategy, buildings use zero carbon electrical energy either generated onsite or supplied by an electrical grid transitioning towards full decarbonization. The carbon intensity of electric power in the UK allows for significant GHG reductions when retrofitting traditional natural gas equipment in buildings to electrically serviced equipment [76, 77]. GHG emissions from electric power generation continue to decrease as grids transition toward net zero carbon. The carbon intensity of electric power in the US is also low enough to allow reductions in emissions through electrification for many applications, including water heating [78].

For decarbonized domestic water heating, the technology receiving the most consideration is heat pumps. Heat pump water heaters operate by extracting heat from one source using air or water, and transferring the heat to an incoming water supply. This enables the heating energy output to be greater than the electrical energy input, as opposed to traditional resistance water heaters where one unit of heat is generated for every unit of electrical energy. The power factor for heat pumps, referred to as the coefficient of performance (COP), depends mostly on the source temperature conditions and the specific equipment characteristics. On average, air source heat pumps are currently capable of producing a COP of 2.5 in UK climates, with ground source heat pumps generally producing a COP of 2.7 [70]. The move toward heat pumps is reversing small storage volume trends for domestic hot water generation back to larger storage. Increasing the storage volume for domestic hot water systems reduces the required output from heat pumps, reducing peak electrical power input as well as generally providing a more economical installation. Existing buildings with low storage, centralized, combustion water heating systems may experience challenges switching to electric water heating equipment due to high electrical loads, lack of space for large storage tanks, and in some cases the structural loads imposed by the storage tanks.

In instances where heat pumps are unable to provide heating, the CCC recommends using hydrogen gas as a replacement for natural gas [74]. Efforts in a number of other European countries are being made to construct municipal hydrogen gas systems by utilizing or replacing existing natural gas infrastructure providing heating energy to buildings. A project in the Netherlands, a country having a fuel share of natural gas similar to the UK [70], began a trial in 2019 involving the production and municipal distribution of hydrogen gas to an apartment building. The apartments provide heating through a hydrogen gas network,

[12]Global warming potential measures the atmospheric heat trapping properties of a greenhouse gas in relation to carbon dioxide.

using the existing natural gas piping in place. The hydrogen is produced from solar electricity through the electrolysis of water, allowing hydrogen to serve as a storage of renewable energy [79]. Keele University in the UK is blending up to 20% hydrogen with natural gas to meet campus heating demands, generating the hydrogen onsite using an electrolyzer powered by renewable energy [80]. An investigation is also underway to convert the natural gas system in the city of Leeds to 100% hydrogen [70]. While carbon neutral hydrogen generation is possible through electrolysis, it currently represents only a fraction of hydrogen in production. Globally, a majority of hydrogen is produced through steam reforming, a process using natural gas or other fossil fuels to separate hydrogen through chemical synthesis. Carbon emissions from steam reforming can be reduced through sequestration technologies such as Carbon Capture Utilization and Storage (CCuS), but this only reduces greenhouse gas emissions at the source of hydrogen production and does not address the greenhouse gas contributions during the production and transportation lifecycle phase. The CCC recommends implementing CCuS technologies for fossil fuel hydrogen production to meet the 2050 emissions target [74].

While the US is not pursuing efforts to decarbonize buildings on a national governmental level, a growing number of cities are independently making commitments to do so through legislation or commitments to enact legislation. Joining 20 other international cities, 8 US cities have signed the C40 Cities Net Zero Carbon Buildings[13] Declaration, committing to enact legislation eliminating greenhouse gas emissions from new buildings by 2030, and in existing buildings by 2050. These cities include Los Angeles, New York City, Portland, San Francisco, Seattle, Washington DC, San Jose, and Santa Monica [81]. San Jose has enacted legislation prohibiting or severely limiting natural gas services in most new construction, beginning in 2020 through electrification of all services [82, 83]. Further supporting the decarbonization of buildings, many states and cities have committed to providing 100% renewable electric power by 2050 or earlier.

5.0 Rainwater Drainage

Storm drainage systems in the UK generally rely on the use of gutters and downspouts, with a considerable amount of resources available for the design of gutters. The utilization of gutters differs from typical US practice, where flat roofs direct rainfall to a central area of the roof to a set of primary and secondary (emergency) roof drains with internal drainage piping. Siphonic rainwater drainage systems are designed to flow full bore at sub-atmospheric conditions and are commonplace in the UK and throughout Europe, though still considered a specialized non-standard system.

While US codes design for one hour rainfall rates with a return period of 100 years, rainfall loadings in the UK are based around a two minute rainfall duration with return periods reflected by four categories, ranging between 1 year and 500 year rainfall events [84]. Guidance from the Environmental Agency suggests accounting for a 40% increase in rainfall volume as a result of changing climatic conditions in comparison to the two minute rainfall events currently published [85]. Rainfall attenuation measures are implemented in many localities under Sustainable Urban Drainage Systems (SuDS) schemes. The London Sustainable Drainage Action Plan features a set of policies that aim to attenuate rainfall drainage and lessen the burden imposed on the combined sewer amidst a growing population and increasingly heavy rainfall events, using green roofs, blue roofs, bioswales, rainwater attenuation tanks [86]. Rainwater

[13]The World Green Building Council defines net zero carbon buildings as being fully powered from on-site or off-site renewable energy sources and achieving high levels of energy efficiency.

attenuation measures are also implemented in a number of localities in the US, particularly on the west coast, and primarily utilize bioswales or planters.

To account for wind driven rain on vertical surfaces of buildings, half of vertical surface areas are required in EN 12056-3 [84] to be added to the associated horizontal rainwater drainage loads. Any vertical surface area above 10 m (32 ft) is ignored in contribution to rainfall loads. This height exception recognizes that wind forces also separate water sheets from the vertical surfaces, counteracting much of the assumed rainfall loads for tall buildings [27]. Diagonal rainfall is compensated in American codes similarly, though without the height exception, leading to overestimations in rainfall design loads for tall buildings [26].

6.0 Water use and efficiency

Over the last century, the UK has shown to have overall higher levels of water efficiency in comparison to the US. Wise reported in 1957 that standard British water closets use 1/2 to 2/3 of the water volume used in American water closets [42]. Two key factors that dictate water use are the water efficiency of the fixture and user behavior. The number of people per household plays a significant role in user behavior due to the sharing of processes such as cooking, dishwashing, and laundry, which tend to decrease the per capita water use as the household size increases. Single person households in the UK have 50% higher water consumption per capita than two person households [87]. Household demographics are comparable in both countries, possibly suggesting that differences in water use are primarily a result of fixture efficiencies and user behavior. Table 7 shows similarities in volume used for faucets and dishwashers in both countries, with usage for washing machines and water closets significantly higher in the US. Another exception to these similarities is the bath, representing 19% of daily water volume in the UK while representing 3% in the US. This disparity can be explained by the popularity of baths in the UK, an example of regional variances in user behavior.

Table 7 – Indoor water use per capita per day by fixture and appliance type

Fixture Type	United Kingdom			United States		
	L	Gal	%	L	gal	%
Bath	28.8	7.6	19%	5.7	1.5	3%
Dishwasher	3.9	1.0	3%	2.7	0.7	1%
Faucets	42.3	11.2	28%	42.0	11.1	23%
Shower	30.0	7.9	20%	42.0	11.1	23%
Washing Machine	16.7	4.4	11%	36.4	9.6	20%
WC	28.8	7.6	19%	53.8	14.2	29%
Totals	**150.5**	**39.7**		**182.6**	**48.2**	

Note: Excludes leaks and water use from equipment such as water softeners
Sources: Future Water, The Government's water strategy for England [88] and Residential End Uses of Water, Version 2 [89]

Water stress, measured by the ratio of annual freshwater water withdrawals to renewable surface and groundwater supplies, is expected to continue increasing globally, reaching a 40% deficit by 2030 [90]. The Environmental Agency projects demand for water in the UK will outpace supply within 25 years and recommends enacting policies to reduce water consumption to 100 L (26 gal) per capita per day [91]. Part G of the Building Regulations requires fixture efficiencies to be selected to ensure that residential occupancies do not exceed 125 L/capita/day (33 gal/capita/day) of water. This can be achieved by either selecting appliances with the water efficiencies shown in Approved Document G (Table 8), or by a calculation method in Appendix A of Approved Document G. This calculation method uses a set of tables for the selection of an appliance flow rate, combined with use factor for the appliance type, to calculate the anticipated total volume used by the fixture per person. Options are also given to offset water use by using graywater or rainwater collection systems. The green building certification program BREEAM, common in the UK and Europe, awards points towards higher certification thresholds for water use reductions of up to 65% of baseline water use [92].

The World Resources Institute projects that significant portions of the western US will experience extremely high water stress by 2030, with withdrawals representing greater than 80% of supplies [93]. To accommodate local water stress conditions, water efficiency measures vary by state and city. Fixture efficiencies are indicated in both model codes (Table 8), with values either being retained after adoption by states or modified for higher efficiency. A majority of states require the fixture efficiencies shown in the model codes, while a number of other states require higher efficiencies. Cities such as San Francisco and San Jose target further reductions in water use with municipal recycled water systems, requiring certain buildings to provide a separate non-potable water service for applications such as water closet flushing and irrigation.

Table 8 – Maximum fixture flow

Fixture Type	British standards	IPC/UPC
Bath	185 L (49 gal)	N/A
Dishwasher	1.25 L/place setting (0.3 gal/place setting)	N/A
Lavatories (metering)	N/A	0.95 L/cycle (0.25 gal/cycle)
Lavatories (private)	6 L/min (1.6 gpm)	8.3 L/min (2.2 gpm)
Lavatories (public)	N/A	1.9 L (0.5 gpm)
Showers	10 L/min (2.6 gpm)	9.5 L/min (2.5 gpm)
Sink Faucets	8 L/min (2.1 gpm)	8.3 L/min (2.2 gpm)
Urinals	1.5 L/flush (0.4 gal/flush)	3.8 L/flush (1.0 gal/flush)
Urinals (automatic flushing)	7.5 L/h to 10 L/h (2 gal/h to 2.6 gal/h)	N/A
Washing machine	8.17 L/kg	N/A
Water closets (single flush)	4.5 L/flush (1.2 gal/flush)	6.1 L/flush (1.6 gal/flush)
Water closets (dual flush)	6/4 L/flush (1.6/1.1 gal/flush)	6.1 L/flush (1.6 gal/flush)

Source: Building Regulations Part L, The Water Supply (Water Fittings) Regulations 1999

7.0 Conclusions

Regional development of standards and design procedures have created unique solutions to address universally applicable plumbing challenges involving fluid mechanics, thermodynamics, and public health. It is clear that two dissimilar solutions can produce acceptable levels of performance, while other solutions may result in lower performance or lack technical justification. Many recommendations in current design standards have been carried over from early standards unquestioned and without revision. The basis for some measures are not well documented or understood, adding further to disagreement between regional methodologies. While the British and two American methodologies each have a certain level of empirically proven performance, shortfalls have been exposed with advancements in plumbing research, as well as increased water efficiencies for fixtures. The prescriptive approaches in design standards have left little opportunity for evaluating new methods, giving special value to regional comparisons between internationally respected design standards. Limited funding for research and testing have presented challenges maintaining the efficacy of design standards, preserving many methodologies based on an understanding of plumbing systems dating back over half a century. Research and testing are not always accepted by regulatory and standards drafting bodies, particularly when at odds with theory supporting traditional methods, often leading to challenges reaching consensus.

Water stress, increasingly heavy rainfall events, and the shift away from fossil fuels require varied adaptive measures, reflecting local climatic projections and the availability of renewable energy sources. These adaptive measures are influencing water use, energy infrastructure within buildings, and rainwater management, requiring a technically robust set of resources available to plumbing and public health engineers. Engineering societies and research institutions such as ASPE, IAPMO, CIBSE, SoPHE, CIPHE, and Heriot-Watt are actively developing and revising design standards to reflect the theory and functionality of plumbing systems in the 21st century. An understanding of plumbing engineering standards and practices from other regions may accelerate the collaborative development necessary to maintain the resilience of plumbing in the new era.

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