NBS TECHNICAL NOTE 966

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Performance Criteria and Plumbing System Design

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Performance Criteria and Plumbing System Design

Technical Note

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FOREWORD

This paper gives the current status of the development of a performance approach to design methods in plumbing. The long-term implication of this performance approach is also discussed.

It is expected that this paper will be of particular interest to plumbing designers and code officials.

As an introduction to the subject, the traditional approach to plumbing system design, based on continuous flow, is reviewed. Then, recent research is discussed in some technical detail in order to explain the significance of time profiles of hydraulic parameters under dynamic conditions (representative of transient flow phenomena in plumbing systems).

The application of performance criteria based on this type of data can reduce excessive design factors and provide useful criteria for evaluating innovative systems. Illustrative examples are given for reduced-size venting satisfying the recommended performance criteria.

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PERFORMANCE CRITERIA AND PLUMBING SYSTEM DESIGN[a]

By M. J. Orloski and R. S. Wyly

ABSTRACT

An overview is presented indicating how the performance approach to plumbing system design can be used to extend traditional methods to innovative systems. Identification of the plumbing performance needed in a built system is used to classify current design criteria intended to furnish this level of performance. Some current design criteria may provide a higher level of performance than is actually needed by the user. In other cases, no standard test method, criterion, or evalution technique exists. Putting existing knowledge into a performance format increases the utility of this knowledge and facilitates identification of needed research to fill the gaps. Some of the mathematical models now used for system design and pipe sizing in plumbing codes are reviewed in the context of performance-oriented research. The results of experimental work in plumbing systems with reduced-size vents (smaller than allowed by codes) are presented as an example of the use of the performance approach, and illustrate a case where performance criteria permit relaxing of vent design practice. Conceivably the re-examination by plumbing designers of traditional design criteria against measured user needs could be beneficially extended to other areas of plumbing design such as water distribution, storm drainage, and plumbing fixtures. Beyond this, it has been recognized that uniform guidelines for evaluation of innovative systems, based on research findings, are essential for wide acceptance of performance methods, particularly by the regulatory community.

Key words: Performance, Plumbing systems, Reduced-size venting

1. INTRODUCTION

The principal objective in the application of the performance approach to plumbing system design and installations is to provide a basis for evaluating the adequacy of alternative methods of achieving satisfactory functional operation for the user. This is accomplished by introducing performance requirements[b] and their related test methods (criteria and evaluation) as a way of facilitating the development, evaluation, and acceptance of innovative systems which are adequate to meet the basic needs of the user.

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[a] Portions of this paper have been presented to the American Society of Plumbing Engineers and the American Society of Sanitary Engineering at their national meetings.

[b] Definitions used in this paper are given in Appendix B, page 52.

In other words, a quantitative statement of what is needed or wanted (a performance criterion) seems better than specifying just one acceptable method of sizing or constructing a given component. However, introduction of performance criteria applicable to a given product or system is difficult because the user's fundamental needs and service expectations have to be identified and expressed in measurable terms. The constraints of the present prescriptive specifications as a basis for systematic improvement of plumbing system design through research are described in the following quote:

> "Neither performance attributes of interest nor the limit states of concern are explicitly expressed in most existing specifications. This lack of clarity has made it difficult to improve specifications through research, as there can be no certainty that a specification provision is improved if neither the response of concern nor the desired performance attribute is clearly defined."[1][c]

In this present paper, the plumbing system and its elements are first discussed generally in the context of user needs and the performance approach, as related to a complete housing system, in order to describe an orderly basis for relating the 'performance attribute of interest' and 'the limit states of concern'. A performance matrix framework is presented in Section 2.1 as a format and a basic tool for systematic identification and classification of the basic user needs (requirements), and of the significant measures (criteria) that may be used for determination of the satisfaction of the requirements. The concept of the existence of both the need and the opportunity to correlate design criteria and performance criteria, in particular through research on plumbing, is introduced in Section 2.2 with a brief review of some of the key mathematical models used in traditional drain-waste-vent (DWV) design and in the establishment of pipe sizing requirements in the codes.

A discussion of the shortcomings of the vent mathematical model for tall stacks (vertical distance of water fall greater than 6 m) as applied to

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[c] Numbers in brackets refer to literature references at the end of paper.

short stacks (vertical distance of water fall less than 6 m) is presented in 3.1. This provides an example of the performance approach in which the practical application of the knowledge that air flow rates predicted by the traditional theory do not occur in systems with short stacks suggests that these pipes are larger than necessary to protect trap seals from effects due to pneumatic fluctuations in the vent. In 3.2, the guidelines are described for the systematic development of performance data in which trap-seal reduction measurement (one performance criterion) is compared with the associated air demand and pneumatic suction in the vent (the traditional design criteria). The recommended sizing criteria resulting from the study are presented in 3.4 and this is followed by a short description of the scope of a subsequent field study for field validation of design criteria based on the laboratory findings.

Major research needs as applied to the plumbing mathematical models in a broad research plan are discussed in 4.1 for the laboratory, and in 4.2 for field investigations. In the conclusions, 5.0, the long-term implications and benefits of utilizing performance methods to supplement traditional methods are presented.

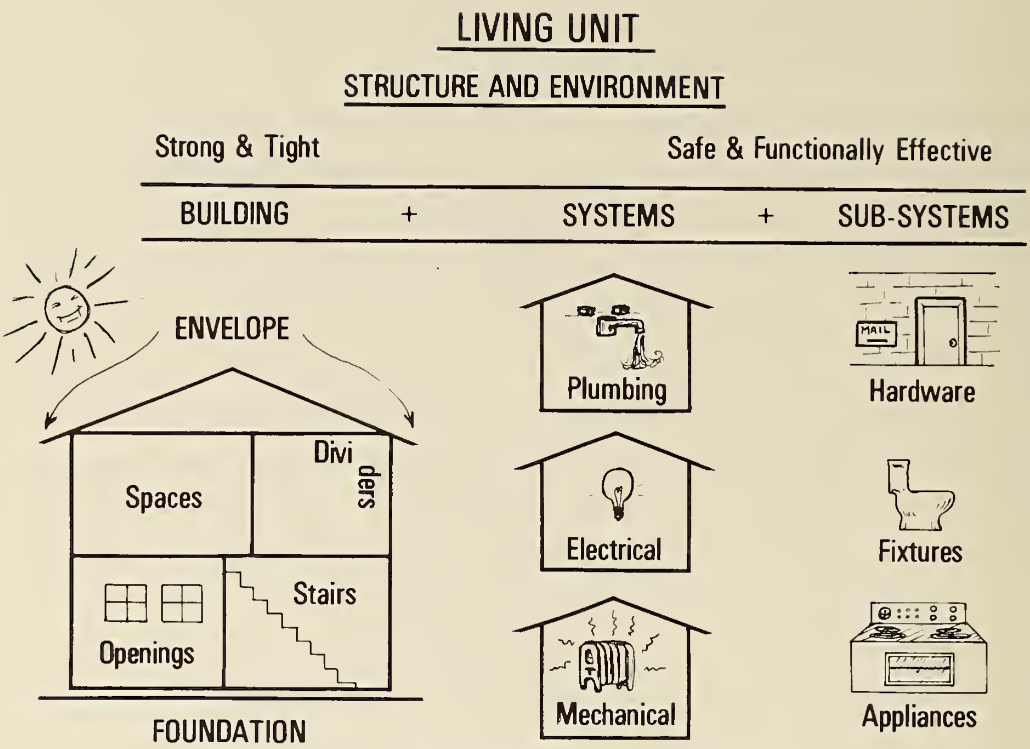
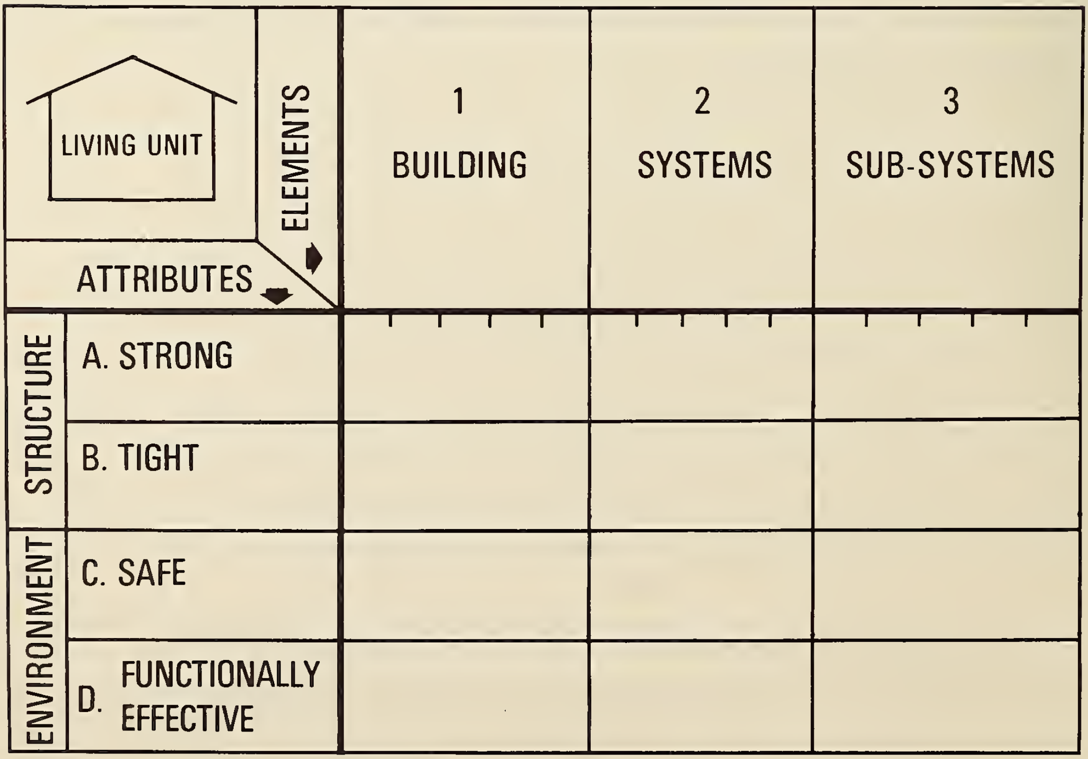


Figure 1. Schematic of Performance Concept of Housing



		1 BUILDING	2 SYSTEMS	3 SUB-SYSTEMS
STRUCTURE	A. STRONG			
	B. TIGHT			
ENVIRONMENT	C. SAFE			
	D. FUNCTIONALLY EFFECTIVE			

Figure 2. Basic Relationship of Elements and Attributes

2. BACKGROUND ON PERFORMANCE-ORIENTED STUDIES

2.1 AN APPROACH TO THE SYSTEMATIC CORRELATION OF USER NEEDS, PERFORMANCE EVALUATION AND DESIGN CRITERIA

In the generalization of the performance approach in relation to a residential building system, the structure and environment together furnish a living unit with certain basic *Attributes*. For the user, a living unit should be Strong and Tight (the structure), and Safe and Functionally Effective (the interior environment). The living unit in turn is comprised of *Elements*: the building, its systems, and their subsystems. See Figure 1. These are interrelated through providing essential utilities for the function of the building to its occupants, see Figure 2, and in turn these parts can be systematically broken down into interrelated components, for a finer and finer grid at all levels of detail, relating back to the overall Attributes of Strong, Tight, Safe and Functionally Effective.

Within these categories, the basic user needs, or qualitative Requirements are enumerated. These Requirements are the primary means by which basic user needs are indexed within the performance framework relating Elements and Attributes. (The examples given in this paper should not be construed as comprehensive or complete.) Figure 3 is an illustrative example of the qualitative Requirements for a plumbing system. Figure 4 illustrates possible criteria for the Requirements of Figure 3, and Figure 5 presents the basic format of RCTC[d] statements for Requirement C2.1.2-2 "Healthful", of Figure 4.

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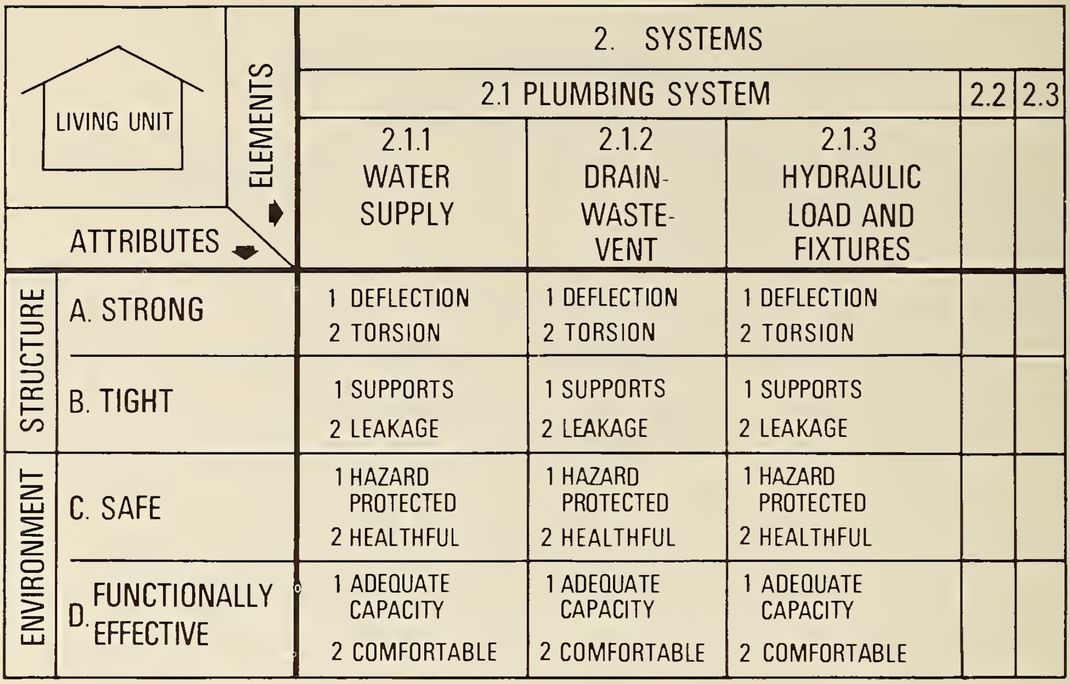
[d] This acronym is defined as follows:

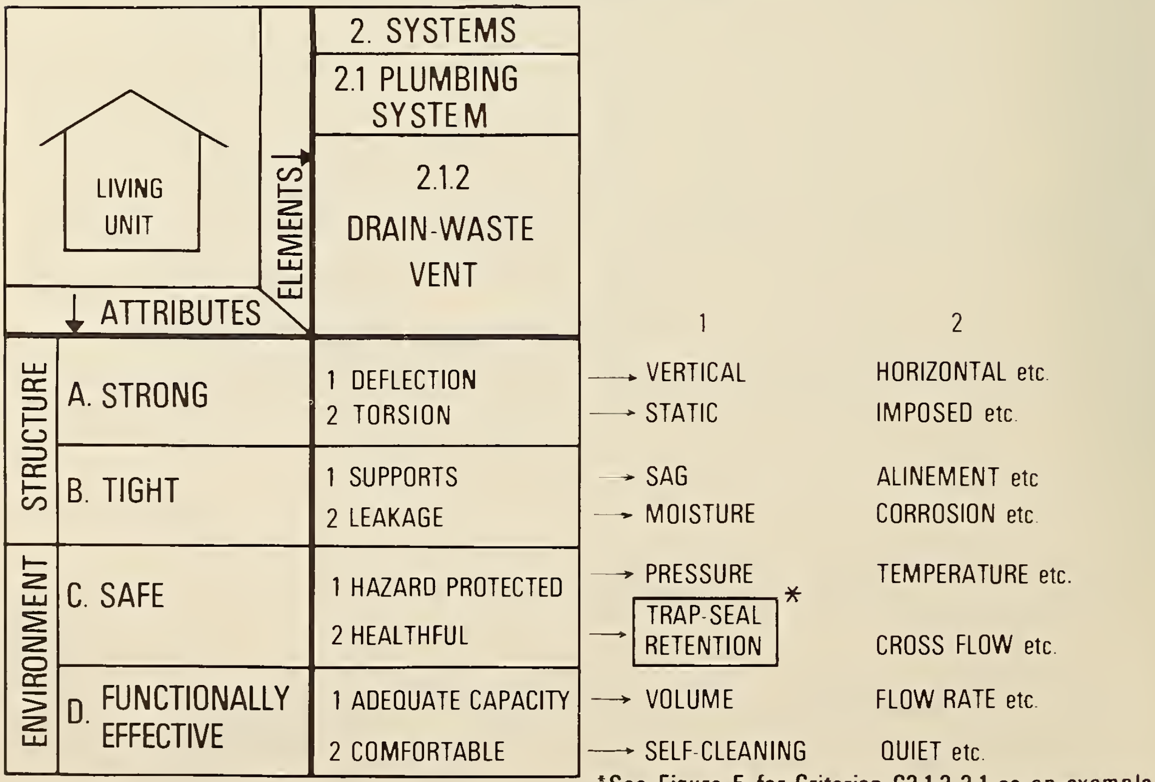
R Requirement
C Criterion
T Test Evaluation
C Commentary

It represents one type of a performance statement format.



LIVING UNIT / ELEMENTS / ATTRIBUTES		2. SYSTEMS				
		2.1 PLUMBING SYSTEM			2.2	2.3
		2.1.1 WATER SUPPLY	2.1.2 DRAIN-WASTE-VENT	2.1.3 HYDRAULIC LOAD AND FIXTURES		
STRUCTURE	A. STRONG	1 DEFLECTION 2 TORSION	1 DEFLECTION 2 TORSION	1 DEFLECTION 2 TORSION		
	B. TIGHT	1 SUPPORTS 2 LEAKAGE	1 SUPPORTS 2 LEAKAGE	1 SUPPORTS 2 LEAKAGE		
ENVIRONMENT	C. SAFE	1 HAZARD PROTECTED 2 HEALTHFUL	1 HAZARD PROTECTED 2 HEALTHFUL	1 HAZARD PROTECTED 2 HEALTHFUL		
	D. FUNCTIONALLY EFFECTIVE	1 ADEQUATE CAPACITY 2 COMFORTABLE	1 ADEQUATE CAPACITY 2 COMFORTABLE	1 ADEQUATE CAPACITY 2 COMFORTABLE		

Figure 3. A General Illustration of Performance Requirements (Qualitative) for Plumbing Systems



LIVING UNIT / ELEMENTS / ATTRIBUTES		2. SYSTEMS 2.1 PLUMBING SYSTEM 2.1.2 DRAIN-WASTE VENT	1	2
STRUCTURE	A. STRONG	1 DEFLECTION	→ VERTICAL	HORIZONTAL etc.
		2 TORSION	→ STATIC	IMPOSED etc.
	B. TIGHT	1 SUPPORTS	→ SAG	ALINEMENT etc
		2 LEAKAGE	→ MOISTURE	CORROSION etc.
ENVIRONMENT	C. SAFE	1 HAZARD PROTECTED	→ PRESSURE	TEMPERATURE etc.
		2 HEALTHFUL	→ TRAP-SEAL RETENTION *	CROSS FLOW etc.
	D. FUNCTIONALLY EFFECTIVE	1 ADEQUATE CAPACITY	→ VOLUME	FLOW RATE etc.
		2 COMFORTABLE	→ SELF-CLEANING	QUIET etc.

*See Figure 5 for Criterion C2.1.2-2.1 as an example

Figure 4. Illustrative Example of 2.1.2 (Drain-Waste-Vent) "Controls" (Measures) i.e. Performance Criteria and/or Evaluation Aids

LIVING UNIT

2 SYSTEMS

2.1 PLUMBING SYSTEM

2.1.2 DRAIN-WASTE-VENT

C. SAFE

■ C. 2.1.2-2 HEALTHFUL (REQUIREMENT)

■ CRITERION C 2.1.2 - 2.1

Trap-seal retention

With water-sealed trap systems, trap seal depth should not be less than 50 mm (2 in) nor more than 100 mm (4 in) and trap seal reductions under loading conditions representative of normal use should not exceed 50 percent of the full-seal depth, in any trap.

■ TEST FOR C 2.1.2 - 2.1

Criteria for selecting test loads for sanitary DWV systems are given as tentative guidelines* . The performance of DWV systems that depend on water-seal traps should be evaluated according to the following:

(a) For self siphonage: Maximum reduction 50 percent trap-seal depth in four successive test runs under identical loading conditions, with the trap refilled before each run.

(b) For induced siphonage (from combined effects of vacuum and back pressure): Cumulative reduction 50 percent trap-seal depth in idle traps, after a series of four successive test runs under identical loading conditions without trap refill.

■ COMMENTARY ON C 2.1.2 - 2.1

In water-sealed trap systems, the important, primary criterion of performance is the ability to maintain the trap seal, not the ability to maintain a specified limit on pneumatic pressure, although there is some relationship between the two. Because the relationships between dynamic pneumatic pressure and trap-seal reduction rate are not adequately defined, it seems reasonable to adopt a maximum trap-seal reduction of 50 percent of the seal depth as the criterion, since a greater limit tends to produce an unstable condition and retention of 50 percent of the seal depth provides some reserve for evaporation, and is adequate to resist entry of sewer gases and foul air under normal circumstances.

*The load selection guidelines presented in Chapter H of [2] were comprised of Table 1a of [3] and two other loading tables which were developed from the Hunter model and certain assumptions.

Figure 5. Example of Basic RCTC Format of Individual Performance Statements

Identifying and ordering basic user needs, or Requirements, within a selected performance framework of Elements and Attributes, however, is only a first step and is primarily an indexing scheme for classifying the information as comprehensively as possible. The key issue is, how is it to be determined whether a Requirement is met?

A performance statement must somehow include what is to be measured. This paper focuses on some simple examples (Figure 5) of one type of performance statement: ■ Requirement, ■ Criterion, ■ Test, and ■ Commentary (RCTC), to point out the importance of standard test methods or other systematic evaluation techniques to determine compliance with a Requirement. The language of performance specifications, and several basic classification methods are discussed in depth in [4].

In an RCTC performance statement, each Requirement has associated with it one or more Criteria. A Criterion denotes some physical or chemical characteristic or property that is subject to measurement and that can be used as a meaningful measure or indication of adequacy in the satisfaction of a performance Requirement. Each Criterion in turn has its own "Evaluation" or "Test" which gives a systematic procedure or test method by which it is determined whether the Requirement has been met, and (Optional) "Commentary" which explains the rationale of the Criterion if this is helpful, or may discuss the limits of the present evaluation approach. Solutions acceptable under the model codes should necessarily be accepted under a performance standard, because such solutions are generally considered to have been found adequate by the test of experience. Ideally, the performance statement (a Requirement, Criterion, Test Evaluation, and Commentary) should contain definitive guidance, preferably in the form of a definitive method of evaluation with acceptance limits, and should be applicable to an innovative method or material. In this paper, "Evaluation" will be used to mean "Test Evaluation" for uniform evaluation techniques including the judgment of a group of persons qualified to make such a determination. If an exact method of evaluation cannot be defined, general recommendations should be provided to reduce subjectivity of evaluation. The present state of knowledge for application of the performance concept is not sufficient, however, for complete coverage of all the plumbing subsystems and conceivable materials. In areas where the state-of-the-art does not yet provide for realistic presentation of performance language, it is very important to evaluate the knowledge concerning the existing specification-type standards as a basis for estimating compliance of innovations with the performance *intent* of these standards, as determined through the combined, studied judgment of experienced persons duly charged with this responsibility.

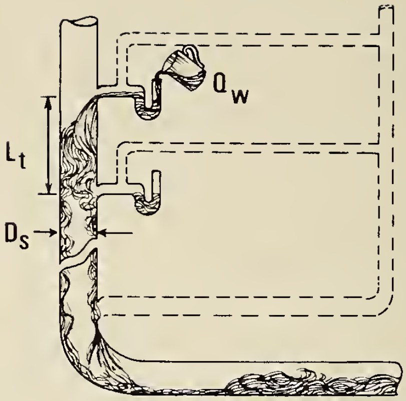
2.2. DISCUSSION OF TRADITIONAL MODELS FOR PLUMBING DESIGN AND THE CURRENT STATUS OF DESIGN MODELS FOR PLUMBING

Examination of certain generally accepted plumbing design criteria shows that design guidelines and limits of acceptability are based on data derived from simple laboratory systems under conditions of continuous flow. Such conditions are nontypical since it is known that dynamic processes predominate. Of special interest is the fact that the models do not relate hydraulic and pneumatic parameters with trap-seal reduction (further discussed in Section 3.2). Much of the accumulated body of data was obtained by methods that could benefit from the more sophisticated measurement techniques now available. In addition, conservative safety factors and simplifying assumptions have been applied in interpreting and utilizing the data in the development of mathematical models, which are a means of generalizing the available data and arriving at a safe level of performance. These mathematical models do, however, provide basic guidelines for the design and acceptance of specific traditional systems which historically are adequate in performance.

In current physical models for plumbing stack design, it is assumed that water is discharged into the stack and, see Figures 6 and 7, after falling a distance L_t (terminal length), reaches a speed V_t (terminal velocity) and clings to the wall in annular flow, for the rest of the fall [5]. Figures 6 and 7 present examples of working equations derived for specific conditions from the more general dimensionally consistent equations given in [5]. Allowable water flow, Q_w, and the associated air flow, Q_a, are

SOIL OR WASTE STACK

(from NBS Monograph 31)



TERMINAL VELOCITY 3.0 - 6.1 m/s (10 - 20 FPS)

$$V_t = C_1 \; (Q_W/D_S)$$

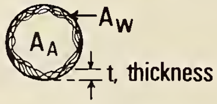
TERMINAL LENGTH 3.0 - 4.6 m (10 - 15 FT)

$$L_t = C_2 \; (V_t)^2$$

WATER FLOW

$$Q_W = C_3 \; (r_s)^{5/3} \; (D_s)^{8/3}$$

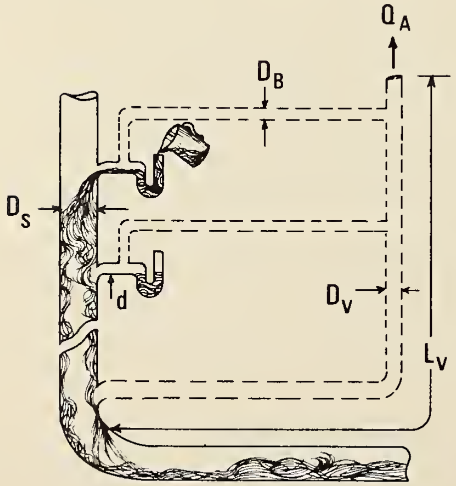
STACK FULLNESS (1/3 to 1/4)



$$r_s = f\,(t, D_S) = \frac{A_W}{A_A + A_W}$$

C_1, C_2, C_3 constants dependent on material roughness

Figure 6. Some Mathematical Models for Soil or Waste Stack Design



VENT STACK

(from NBS Monograph 31)

LENGTH OF VENT

$$L_V = C_4 \; (D_V)^5 / Q_A^2$$

(for a 0.25-kP_a (1-in. W.G.) pressure drop)

AIR FLOW RATE

$$Q_A = C_5 \; (r_S)^{2/3} \; (1 - r_S) \; (D_S)^{8/3}$$

MINIMUM BRANCH VENT DIAMETER

$$D_B = D_V/2 \text{ or } D_S/2$$

whichever is less *but* not less than 35mm (1¼ in)

C_4, C_5 constants dependent on material roughness

Figure 7. Some Mathematical Models for Vent Stack Design

computed by the assumption of a stack fullness ratio, r_s (area of the water ring to the internal area of the pipe) and ratio of mean air speed to water speed, V_a/V_w. Allowable vent length, L_v, or diameter, D_v, (one of these must be assumed) is computed on the basis of the peak demand air flow, Q_a, the allowable pressure drop, dP, and a material-dependent roughness factor. In the design of drain-waste-vent systems, the traditional limit of air pressure fluctuations has been ± 0.25 kPa (± 1.0 in W.G.)[e] [6, 7]. (However, in terms of the fundamental need, or Requirement, of the user for protection of health, this implies adequate trap-seal retention.)

In the design practice for nominally horizontal sanitary drains it is assumed that the water in the drain should flow at a mean velocity not less than 0.6 m/s (2 ft/s) when one-half full, and should not in any event flow more than one-half full under design load [8] (see Figure 8). A complicating factor in the design of horizontal lines is the 'hydraulic jump' which is not well defined through adequate mathematical models. The Manning Formula for uniform continuous open channel flow is not appropriate for the dynamic system, nor is the relationship of the hydraulic jump to stack capacity well understood for transient flow. A hydraulic jump is an energy dissipation phenomenon in a nominally horizontal conduit (pipe or channel) by which the depth of flow (in the downstream direction) increases suddenly, possibly filling the cross section of the conduit. Development of insight into and understanding of this phenomenon in plumbing systems is important in the evaluation of some innovative systems (single stack systems, for example) where a full building drain and back pressure at the base of the stack can choke air circulation, and cause ejection of sewage through floor drains or other fixtures connected near the base of the stack.

In previous studies of horizontal drains at NBS [8], a controlled surge flow was utilized in a horizontal drain as a means of simulating a hydraulic jump and some of its effects. In general, cresting of the jump occurred much further downstream of entrance than the 10 drain diameters commonly assumed [9]. It was found that as the duration of the surge was

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[e] Units and conversion factors are given in Appendix C, page 54.

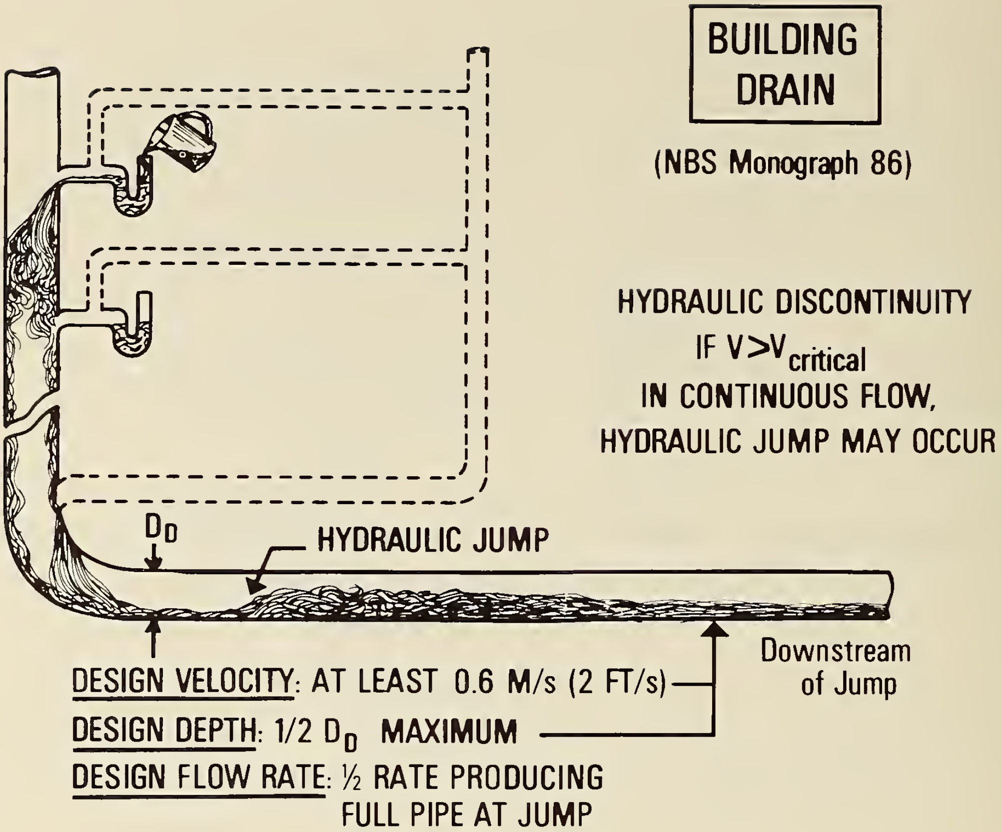


Figure 8. Principal Parameters for Design of Horizontal Drains

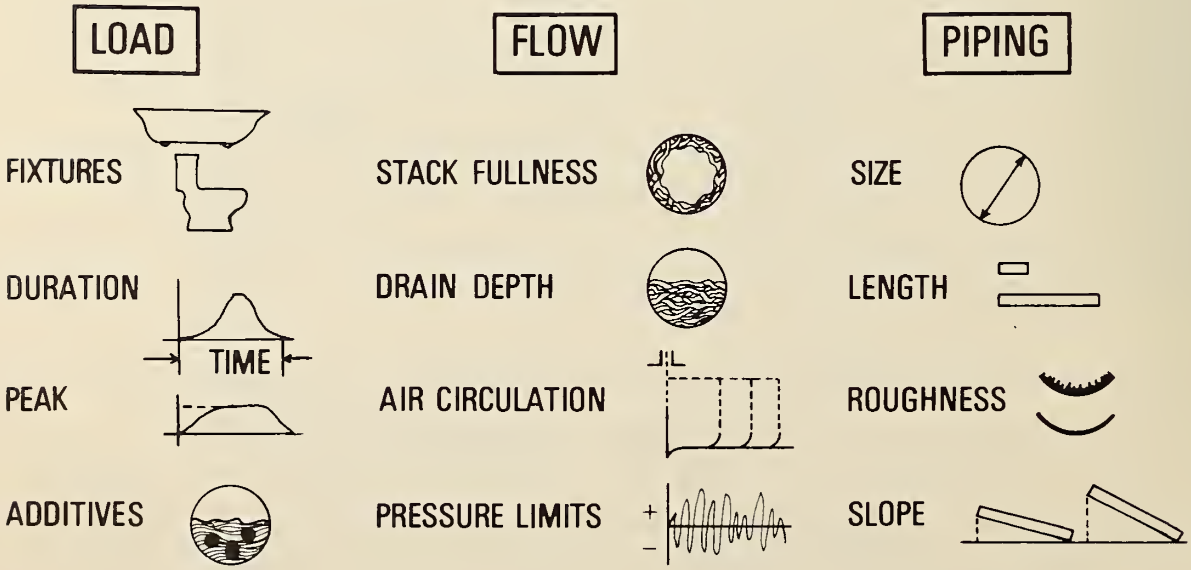


Figure 9. Variables in System Capacity

decreased, the capacity of the drain to carry the flow without completely filling, was increased. Also, this relative increase in drain capacity was inversely proportional to the drain slope.

A further study is needed of the dynamics of this type of flow especially in relation to stack load conditions. Such a study could provide a better understanding of the dynamics of the plumbing drainage system at the base of the stack where the horizontal drain (designed for 0.6 m/s) may not be capable of receiving a continuing discharge from the stack (designed for 3.0 - 4.6 m/s). A more general definition of conditions determining the drain capacity in this type of experimentation is needed and a more realistic application of the laboratory data depends on improved definition of the representative time-profile of the surge from data under field conditions. This is discussed further in 4.2.

To focus on the system as a whole, Figure 9 depicts the basic parameters associated with hydraulic load profile (i.e. load vs time) and hydraulic carrying capacity. Many of these have been discussed in part in Figures 6, 7 and 8. Perhaps the analogy of the changing traffic load pattern across a bridge would be helpful in describing the time profiles of hydraulic parameters. The hydraulic load profile corresponds in the analogy to the changing vehicular traffic pattern (Load in Figure 9) on a bridge, while the hydraulic carrying capacity may be described both as analogous to achieving smooth movement on the bridge without stoppage of the probable maximum number (design load) of vehicles that will be carried simultaneously (Flow in Figure 9) and to maintaining the strength of the bridge (Piping in Figure 9) for the peak loads during the loading period.

The design hydraulic load in plumbing systems is derived from the discharge rate calculated from the estimated use of the plumbing fixtures in the system. The frequency with which this peak design load occurs has been difficult to document in real systems under service conditions. It is, however, widely believed that the customary Hunter Curve [10, 11, 12] load-estimating calculations result in pipe sizes larger than needed for proper functioning of the plumbing system.

In transporting the hydraulic load, two flow parameters, stack fullness (r_s) and water depth in the drain (H_d) are primary determinants of the hydraulic carrying capacity. Design values of r_s and H_d (these are related to the volume rate of water flow) in turn affect the type and assumed amount of venting (volume rate of air flow) needed. The purpose of venting the wet system with air is to preserve the fixture trap seals from suction (self or induced siphonage), and back pressure. To this end, pneumatic pressure excursion in the system is limited by design to ± 0.25 kPa (± 1.0 in W.G.). Actually, these pressure excursions affect the calculated air demand, Q_a (a pressure drop value is included in constant C_4 of Figure 7), and also limit allowable connected fixture (unit) loads (which are a function of design peak water flow rate, Q_w).

The pipe size directly affects r_s in vertical flow and H_d in horizontal flow, for a given flow rate. The overall configuration of the system is also important. Straight pipe of proper size, without fittings, offers the least resistance to flow. Changes in direction, the presence of fittings, changes in pipe length and slope will alter the carrying capacity of the system. New, smooth pipe offers the least resistance to flow, but documentation of the increase of effective pipe roughness over time in plumbing drains and vents and its limitation on the fluid carrying capacity (of the pipe) would permit better prediction of carrying capacity under service conditions. Some engineers have recommended an adjusted vent diameter based on observed fouling in service in applying the equations of Figure 7, but this is not standard practice.

In summary, the relationships between design parameters and performance are not adequately accounted for in present design practice, due to the lack of definition of some relevant phenomena and due to the fact that significant correlations between some of the parameters are either not recognized, or are not satisfactorily established. As an example of an incomplete correlation, taking into account the reduction in cross-sectional area due to fouling in service may tend to increase design sizes of new pipe, but a better definition of the dynamic hydraulic carrying capacity may tend to decrease the design sizes of new pipe.

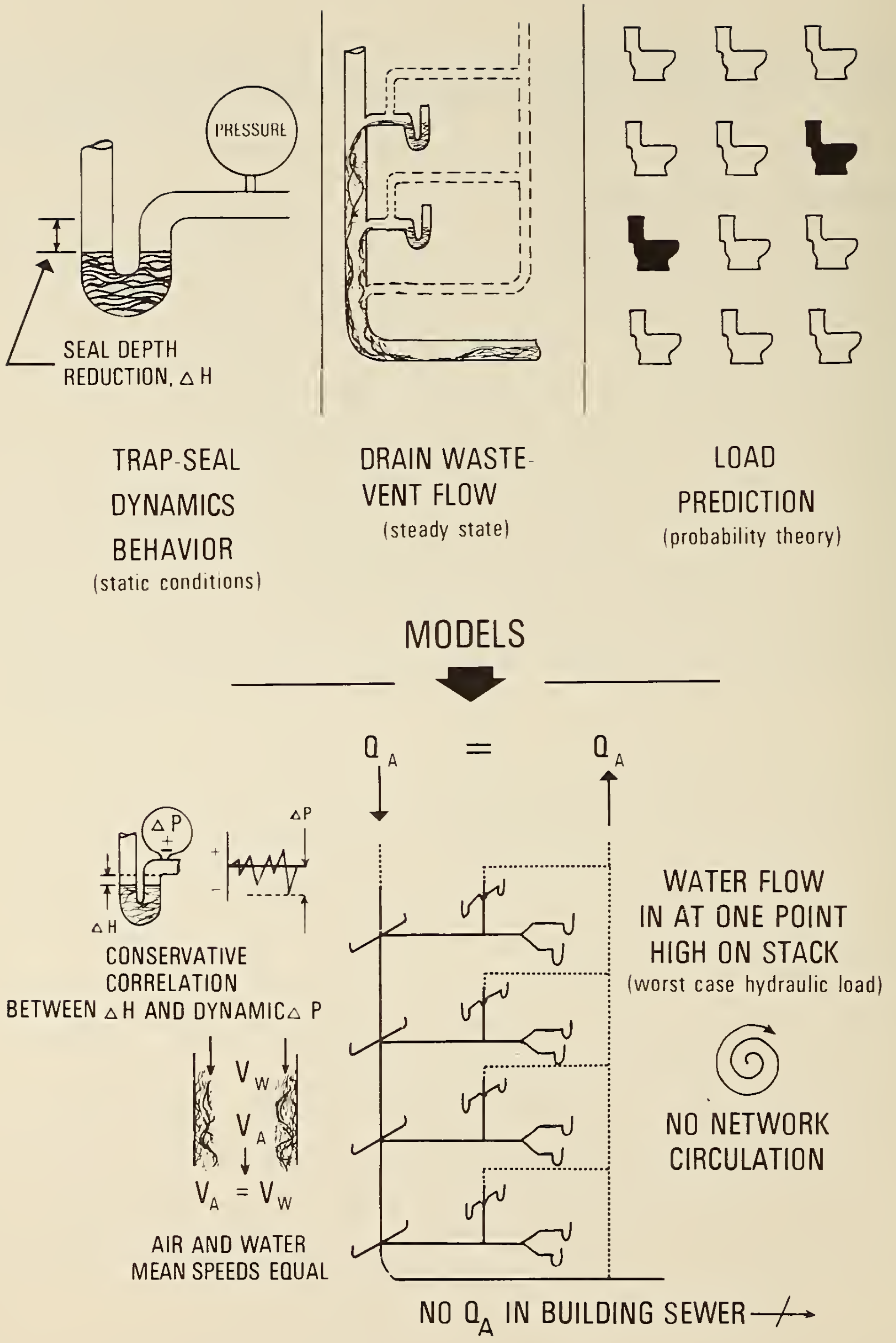


Figure 10. Arbitrary Assumptions in Applying Mathematical Models to Vent Design in Tall Stacks

3. EXAMPLE OF PERFORMANCE RESEARCH IN PLUMBING AND ITS APPLICATION TO PLUMBING DESIGN

3.1 DISCUSSION OF TRADITIONAL VENT MODEL FOR TALL STACKS IN SHORT STACK APPLICATIONS AND NBS STUDIES OF SHORT STACK SYSTEMS

Having briefly reviewed the broad framework within which performance criteria may be identified and ordered with regard to basic user needs and to the framework of traditional plumbing design, an illustrative example of a performance-oriented study will be presented using the NBS work on venting criteria.

In traditional systems, it is customary that a continuous air path be maintained within the system from roof to sewer. This is provided through design, as discussed in Section 2.2, that seeks to maintain a core of air within the falling water in the stack, and to limit the peak water depth in the building drain and sewer to a depth about 1/2 the pipe diameter. In traditional design, however, no definitive account is taken in calculated air demands of the fact that in many systems, particularly with short stacks, air demand is significantly reduced (from that predicted from the usual model [5]) by pneumatic pressures differing slightly from atmospheric pressure, but still within the ± 0.25 kPa code-prescribed limit. Thus many systems are designed for calculated air flow rates much greater than actually occur under particular pneumatic conditions, because the assumption is made that the pneumatic pressure does not differ from atmospheric, and this makes Q_a a maximum value which is utilized in the vent sizing equation to give a maximum size of vent.

Furthermore, the basic assumptions [5] in accepted venting theory drawn from the mathematical models for calculated air demand in tall stacks that have been described are especially conservative for systems with short stacks -- water fall distance less than 6.1 m (20 ft). These assumptions, depicted in Figure 10, are: (1) all the air brought down the soil (or waste) stack with falling water from discharging fixtures is exhausted in an equal amount out the top of the vent stack, without losses; (2) there is no slippage between the air and water during fall in the stack (i.e. mean speeds of air and water assumed equal); (3) worst case hydraulic load (with all the water introduced at the top of a tall stack in most of the tests) was utilized in experiments from which air demand data were drawn; and (4) no specific contribution to venting was assumed either from air circulation within the vent network or relief from the building drain and sewer.

The calculation of air flow rates under the above assumptions made in venting theory for tall stacks led to designs of oversize vent pipes for many residential (short stack) designs. For this reason, a planned laboratory study of hydraulic and pneumatic parameters in systems with reduced-size vents was undertaken. The National Bureau of Standards has been carrying out laboratory work on reduced-size vents (smaller than those presently allowed by model plumbing codes) over a number of years. The earliest laboratory work was sponsored by the National Association of Home Builders, and more recently by the Tri-Services Investigational Committee on Building Materials of the Department of Defense.

In the early work, two full-scale systems and several partial DWV systems were studied [13]. The principal measurement in the full-scale system was trap-seal retention (a performance criterion). Principal measurements in the partial DWV systems were peak air flow rate and corresponding pneumatic pressure in the vent (design criteria). This investigation provided an empirical basis for further work to broaden the vent-sizing criteria developed from the initial work so as to apply to individual and branch vents, and to differentiate between vent sizes for one- and two-story configurations [14].

In the more recent laboratory investigation, a full-scale two-story "mixed" system (where the pneumatic suction affecting the P-trap was the limiting performance criterion) was studied, see Photos 1 and 2, after first experimenting with a simple component stack with flushometer water closets which was used to isolate the water closets in order study pneumatic suction related to water-closet trap-seal performance [14]. Test loads in the

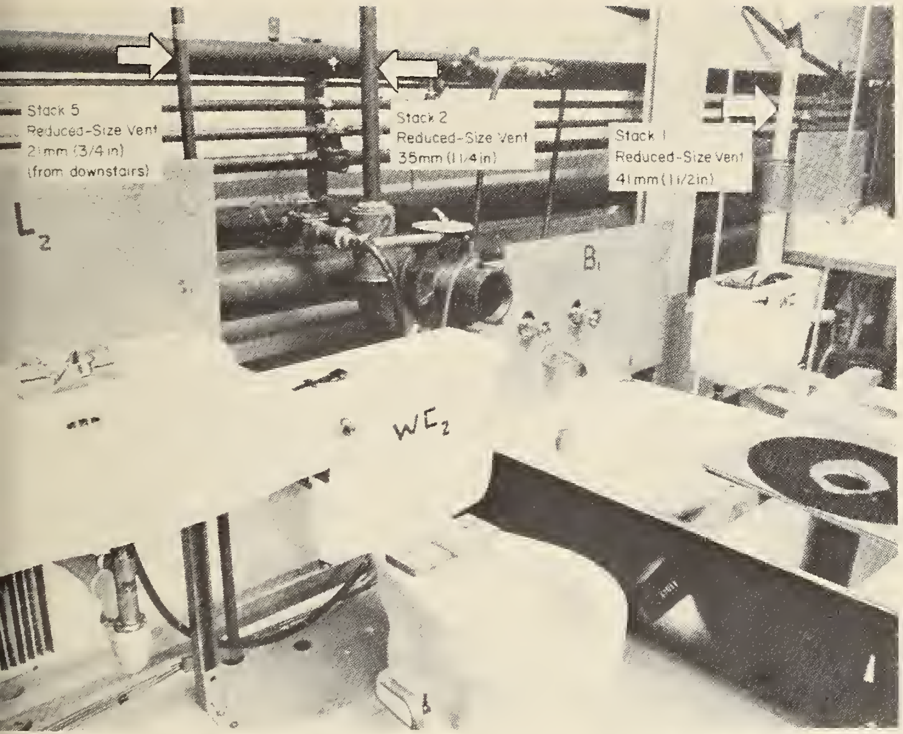


Photo 1.

NBS Laboratory Townhouse,
Second-Story Fixtures

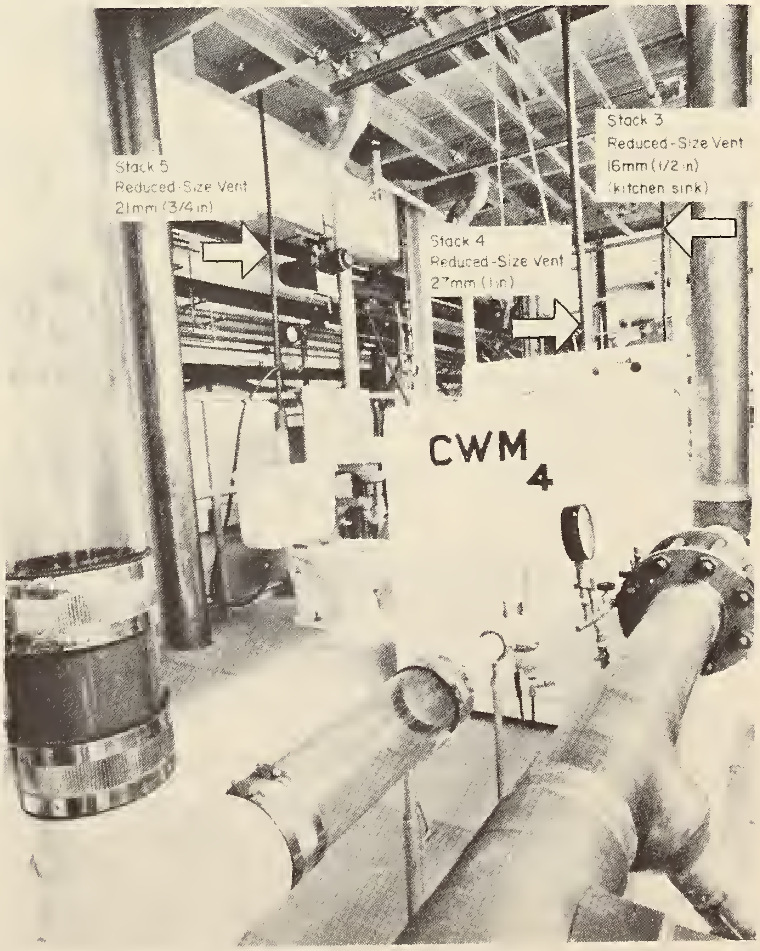


Photo 2.

NBS Laboratory Townhouse,
First-Story Fixtures

full-scale system selected on the basis of guidelines given in [3] covered a wide range of operating conditions from normal to severe loadings including some tests with the vent terminals closed and a few tests with the building drain submerged. (Tests with the building drain submerged and an adequate range of tests with additives were not included in the earlier NBS-NAHB study.

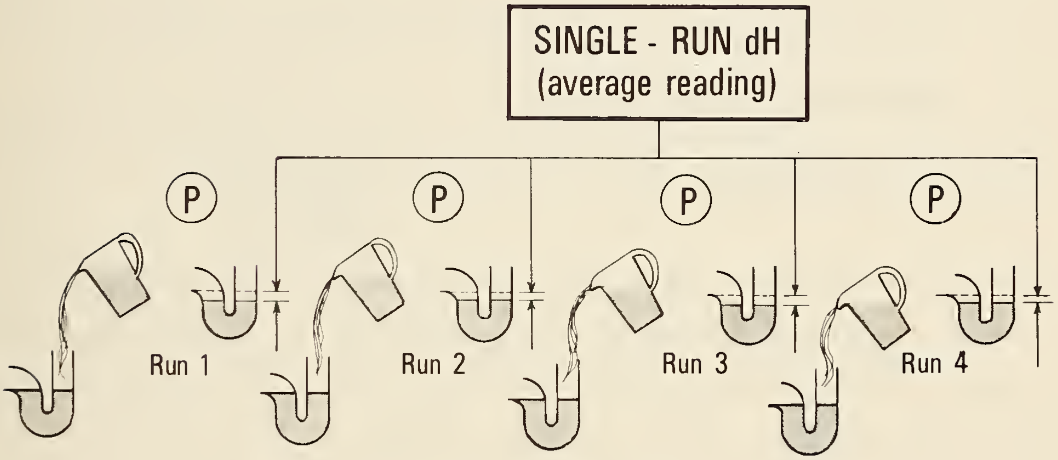
In the recent tests, the experimental approach was to obtain a correlation under dynamic conditions between the peak vent suction (0.2 s averaging period), the peak air flow (0.2 s averaging period), and P-trap and WC-trap trap-seal reduction. The averaging period refers to the time period selected for measurement for which the (data acquisition system) computer would retain a single value of the (pressure, air flow rate or building drain depth) parameter representing an average value of the many values scanned in that time period. The broad need for systematic research for better definition of time profiles of hydraulic and pneumatic parameters in relation to values obtained under conditions of continuous flow is discussed further in 4.1.

3.2 DEVELOPMENT OF LABORATORY PERFORMANCE DATA FOR ONE CRITERION

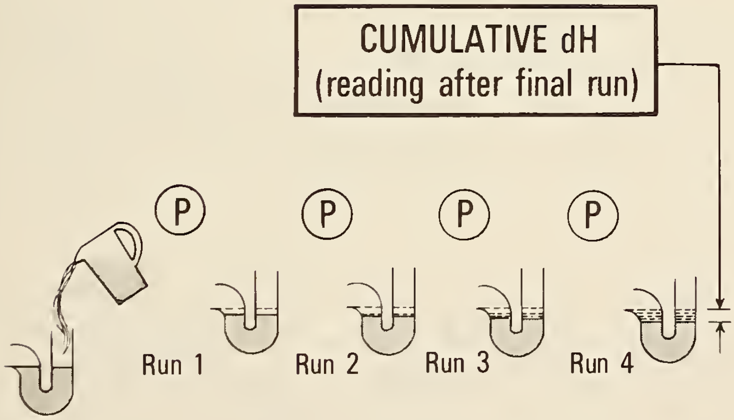
A systematic approach to measurement which is reproducible and accurate is essential for the collection of performance data if such data are to have a general applicability. As discussed in Section 1.1, the uniform evaluation guidelines for judging the compliance of a system to a performance Requirement are important in order to assure an evaluation technique which will have general applicability from system to system.

The basic procedure that was followed in the recent laboratory tests was to discharge a pre-selected combination of fixtures four times (four runs) and to record selected peak pressures and to read the idle traps after each run. This gave a cumulative value of trap-seal reduction after four runs. In some cases, the traps were refilled before the beginning of each run and the (4) values averaged. This produced a single-run dH value. These evaluation procedures are described in the Test section of Figure 5. The procedures are depicted schematically in Figure 11.

SYSTEMATIC TEST PROCEDURES FOR TRAP-SEAL REDUCTIONS, dH
(TEST = FOUR RUNS = 1234)



(TEST FOR C 2.1.2 - 2.1 (a))
from Figure 5



(TEST FOR C 2.1.2 - 2.1 (b))
from Figure 5

Ⓟ PEAK PRESSURE OBSERVED OR RECORDED DURING RUN (OPTIONAL)

Figure 11. Difference Between "Single-Run" and "Cumulative" Measurements of Trap-Seal Reduction (dH). (In each case, the peak pressure (dP) is averaged for the four runs.)

Development of these guidelines for deciding what and how measurements are to be made is an evolutionary process both analytical and empirical. As mentioned in Section 2.2, the current mathematical models for plumbing design do not specifically relate pneumatic pressure fluctuation and trap-seal retention. Rather it is assumed that vent sizes calculated to limit pressure drop to 0.25 kPa are required to protect trap seals. In the NBS Laboratory studies of reduced-size venting, the limit of acceptable trap-seal reduction was set at 25 mm (1 in) as representative of the performance intended in service. During the tests, the pneumatic peak suction in the vent was measured also, for comparison with the values predicted for air flow at a 0.25 kPa pressure drop [5] from theoretical computations.

In the recent NBS laboratory work, a component stack comprised of a 5.5 m (18 ft) long 78 mm (3 in)[f] diameter PVC stack with back-to-back flushometer water closets at the top was studied initially. Test conditions could be carefully controlled in this simple configuration. An adjustable butterfly valve was used to simulate the resistance of different sizes or lengths of vent pipe. A schematic of the simple system showing the measurement points is given in Figure 12. Tests (4 runs per test) were first carried out with the butterfly valve open, then with 3 different degrees of restrictio and finally with the valve closed, each series for supply line pressures 207, 345, 483 kPa (30, 50, and 70 psi). Each water closet was flushed 4 times alone, then both were flushed 4 times together, for each valve setting, in general.

In Figure 13, the data from the single WC flushes in the simple system is presented. Of special interest is the much smaller rate of increase in the trap-seal reduction (dH) values than in the peak vent suction (dP) values, as the valve is closed. In particular, the peak vent suction, dP, is 1.00 kPa (4.0 in W.G.) for a 25 mm (1.0 in) trap-seal reduction, dH, for

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[f] The metric size equivalents given are simple conversions of the nominal pipe sizes in the U.S. Customary Units, and therefore do not represent either actual or nominal metric pipe sizes.

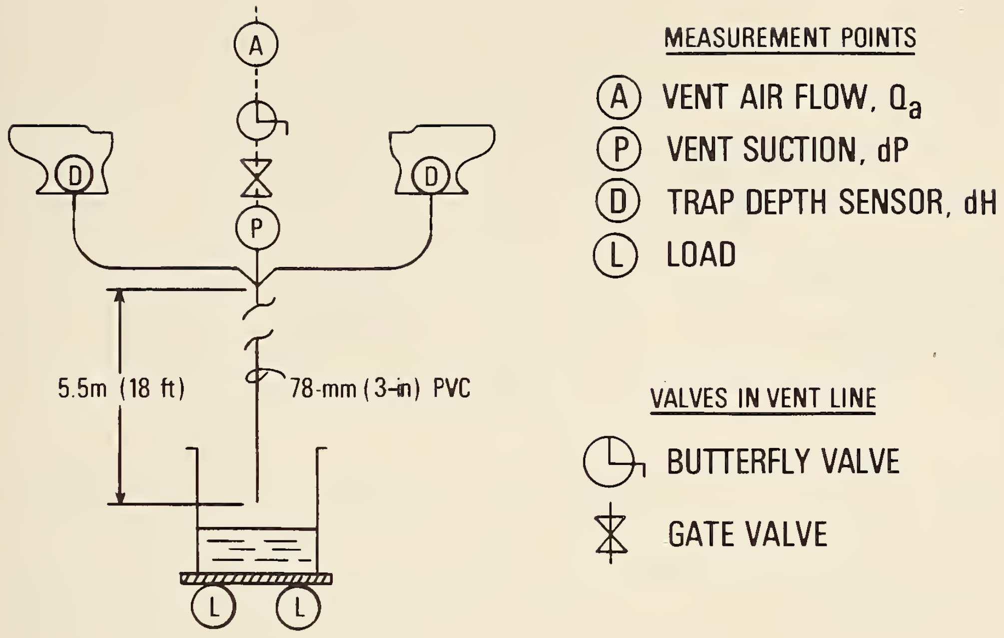


Figure 12. NBS Laboratory Component Stack Schematic

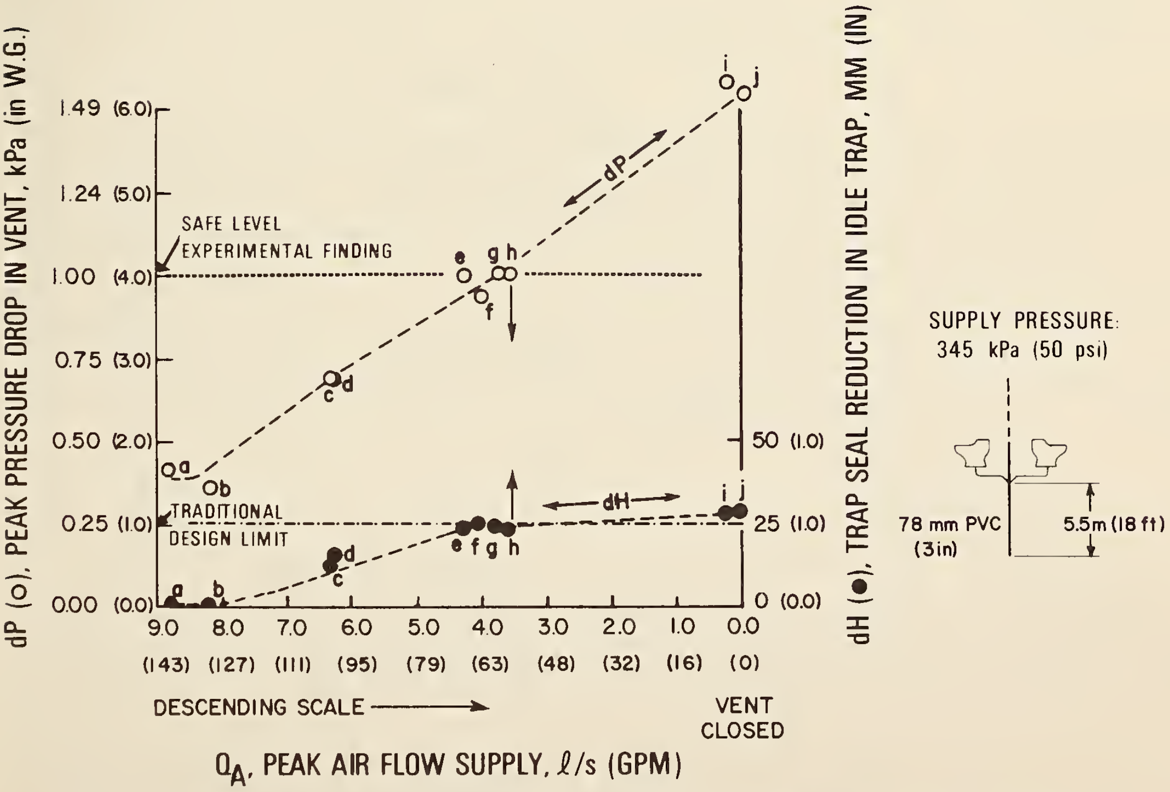


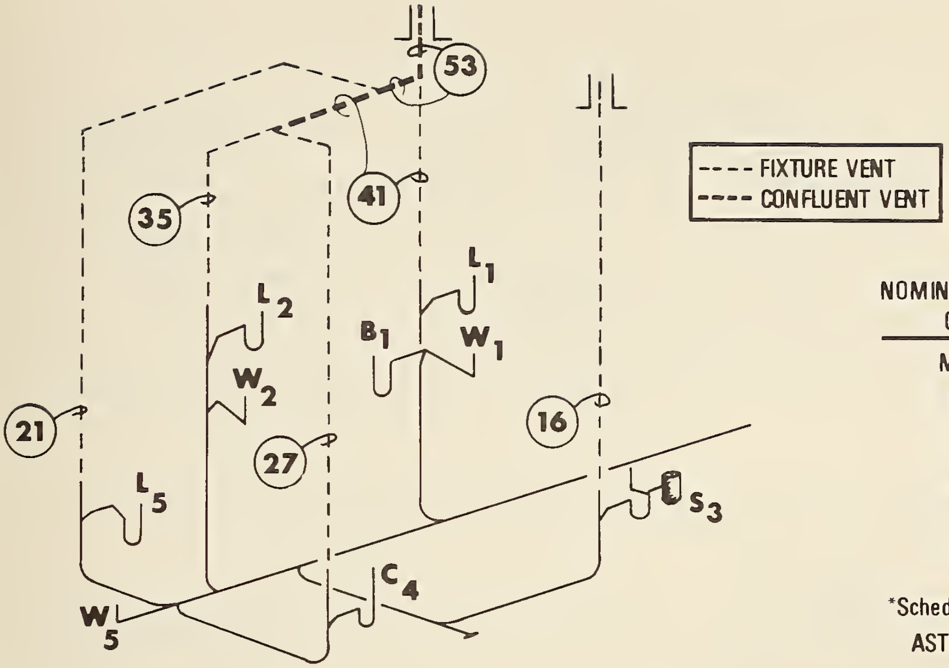
Figure 13. Component Stack Data With Flushometer Water Closets

single flushes. Also important, but not shown in Figure 13, is that the corresponding peak vent suction, dP, for four runs *without* refilling the idle trap between runs, was 0.75 kPa (3.0 in W.G.) for a 25 mm (1.0 in) cumulative trap-seal reduction, dH. In other words, a single WC flush which produced (in the restricted vent) a peak suction level in the vent of 1.00 kPa (4.0 in W.G.), or four consecutive flushes (no refilling) that each produced a peak suction level in the vent of about 0.75 kPa (3.0 in W.G.) reduced the idle WC trap seal in the back-to-back configuration by 25 mm (1.0 in).

After completing the study of the simple system, a full-scale two-story townhouse system was tested in the laboratory. A schematic of the townhouse system shows the geometry and fixture distribution of the system (Figure 14). The reduced-size vent sizes are marked. The system had 9 fixtures; one and a half bathrooms upstairs, and a half bath plus a kitchen sink and clothes-washer downstairs, see Photos 1 and 2. The system was tested over a variety of conditions including one with the main vent terminals closed and the building drain submerged. Reduced-size vents were installed 152 mm (6 in) above the flood rim of the fixtures served.

Because of the mild suctions produced in the townhouse system under representative test loads, data relating pneumatic pressure excursion and trap-seal reduction near trap-seal failure levels were not numerous. In this system of mixed fixtures, the P-traps failed more readily than the WC-traps. Trap failures occurred only when the vent terminals were completely closed, in accordance with the test plan. Figure 15 gives specific information about the dP-dH relationship for P-traps in the failure region.

For a representative test with the vent terminals closed, the time profile of the pressure level of vent suction is presented in Figure 17, with the corresponding cumulative trap-seal reductions of the idle fixtures. The data (fed to an on-line plotter from a mini-computer which processed the



NOMINAL PIPE-DIAMETER CONVERSIONS

MM	IN*
16	½
21	¾
27	1
35	1¼
41	1½
53	2

*Schedule 40 pipe, ASTM D2665

Figure 14. NBS Laboratory Townhouse System Schematic

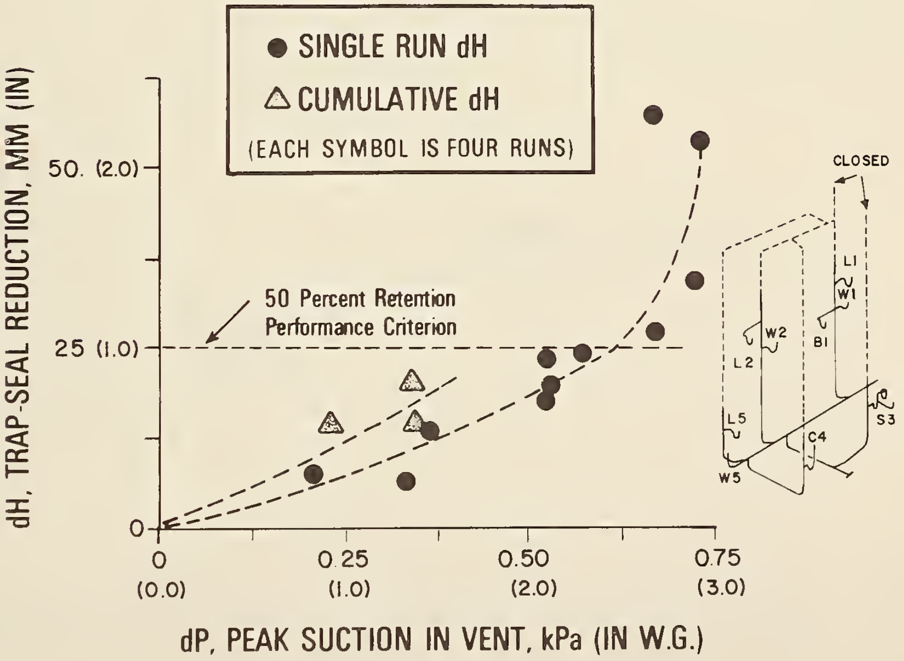
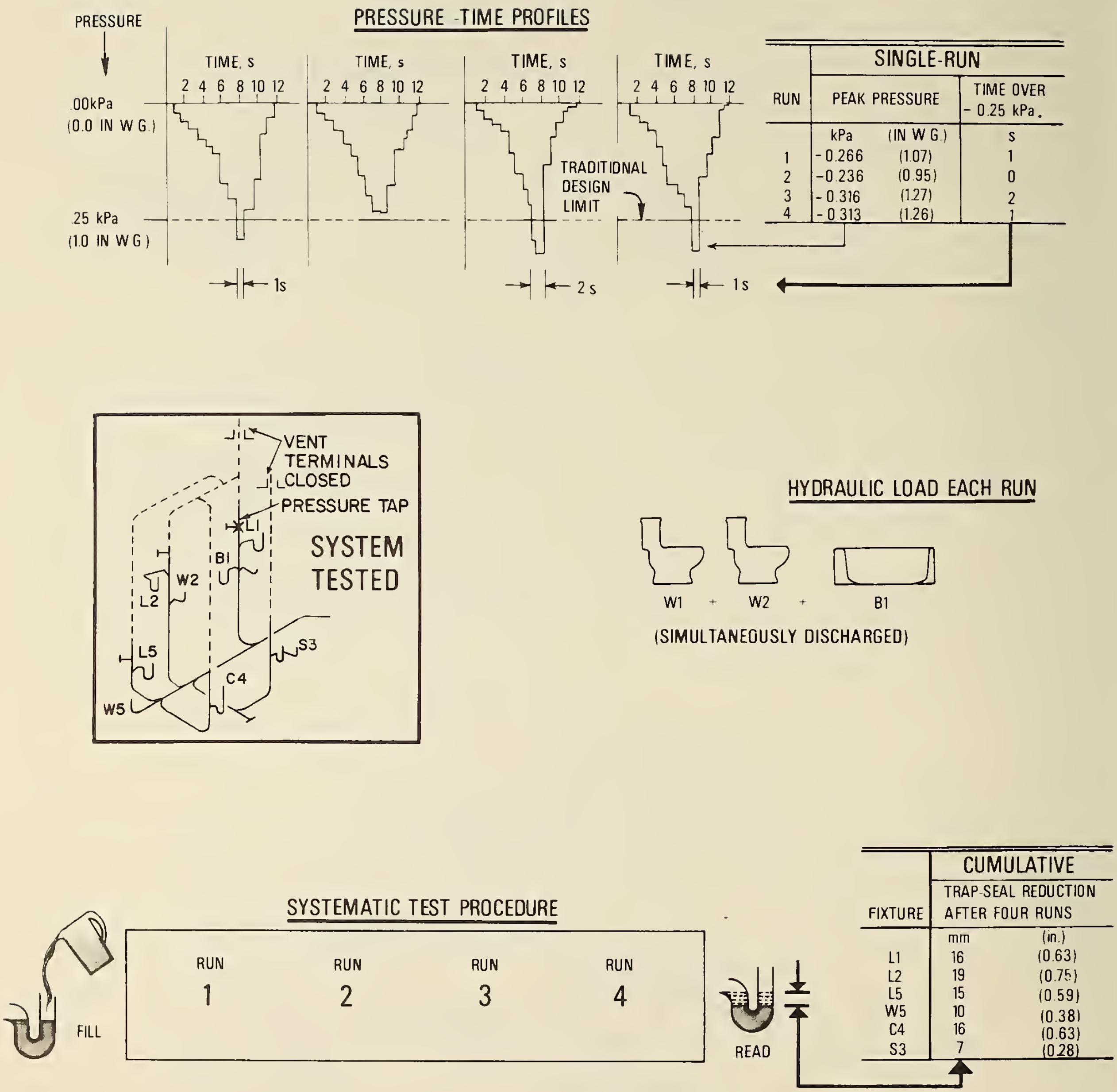


Figure 15. Townhouse System Data on P-traps



RUN	SINGLE-RUN		
	PEAK PRESSURE		TIME OVER - 0.25 kPa.
	kPa	(IN W G.)	s
1	- 0.266	(1.07)	1
2	-0.236	(0.95)	0
3	- 0.316	(1.27)	2
4	- 0.313	(1.26)	1

FIXTURE	CUMULATIVE TRAP-SEAL REDUCTION AFTER FOUR RUNS	
	mm	(in.)
L1	16	(0.63)
L2	19	(0.75)
L5	15	(0.59)
W5	10	(0.38)
C4	16	(0.63)
S3	7	(0.28)

Figure 16. Sample of Data for a "Time Slice" Averaging Period of 1.0 s Duration and the Associated Cumulative Trap Seal Reductions (dH) from a Four-Run Test (i.e. systematic procedure of Figure 11)

data to a single average value for each 1-second "averaging period") represent the peak suction produced in the soil stack vent for a discharge of two water closets and a bath tub, all in the second story level. The greatest trap-seal reduction was 19 mm (0.75 in) even though the suction at the measured point was over 0.25 kPa (1.0 in W.G.) for a cumulative time of 4 seconds for the four runs. These data provide additional evidence to that of Figures 13 and 15 that idle trap seals can tolerate repetitive, brief applications of rapidly oscillating suction beyond the traditional design limit value of 0.25 kPa (1.0 in W.G.).

3.3 DISCUSSION OF FINDINGS ON FLOW PARAMETERS AND TRAP PERFORMANCE

Results from the experimental work indicated that both the vents and building drain were important elements of the air circulation network. Empirical data were obtained in the townhouse tests indicating the presence of recirculation within the vent network, and of a difference in the peak air demand from a first or second story discharge. These data are given in Table 1, an excerpt of Table 9 in [14]. It is believed air circulation within the vent-drain network, with the main vent terminal closed, furnished the air flow required by the operating fixture since the levels of vent suction measured were nearly the same for both open and closed vent terminals.

Table 1. HEIGHT OF FALL EFFECT AND AIR CIRCULATION EVIDENCE

(0.2s Averaging Period)*

Water Closet Discharged		TEST CONDITIONS							
		VENT OPEN				VENT CLOSED			
Name	Location	Q_a, peak air demand at vent terminal		dP, peak vent suction in stack of active fixture		Q_a, peak air demand at vent terminal		dP, peak vent suction in stack of active fixture	
		(l/s)	(gpm)	kPa	(in W.G.)	(l/s)	(gpm)	kPa	(in W.G.)
W2	Second story	(1.8)	28.	0.082	0.33	0	0	0.062	0.25
W5	First story	(0.5)	8.	0.010	0.04	0	0	0.006	0.02

* This averaging period is different from that for Figure 16. See also Section 4.1.

A depth monitor was utilized in the tests to measure the peak water depth in the building drain, intended by design not to exceed one-half drain diameter at design flow rate. For a discharge of four fixtures, the most fixtures used in a test an unlikely load the measured water depth in the nominal 4-in building drain was a maximum of 6 cm. The hydraulic load producing this level was: W1 + W2 + W5 + S3A, i.e. the simultaneous discharge of the three water closets and one bowl of the double-bowl kitchen sink.

As a summary of the experimental relationship of trap-seal performance and pneumatic pressure, data are presented in Table 2, giving a comparison of the different levels of peak suction producing a 25 mm (1.0 in) trap seal reduction in WC traps and P-traps, for single and multiple flushes. Although a water closet trap can tolerate a higher level of peak suction (to produce a 25 mm trap-seal reduction) than a P-trap, the P-trap criterion is the limiting value in a system of mixed fixtures. The finding is based on the data from reverse trap water closets having trap-seal depth of approximately 76 mm (3 in) and 1 1/2-in P-traps having trap-seal depths of a approximately 51 mm (2 in). Another experiment, made on a ten-story system, [15], indicated that WC-trap-seal depth may be the limiting criterion for back pressure.

Table 3 presents a summary of the principal results, in terms of trap-seal performance, of the tests on the full-scale system following the systematic test procedures of Figures 5 and 11. There were no trap-seal reductions of significance unless the main vent terminal was closed.

The recommendation for a design value for dP of 0.37 kPa (1.5 in W.G.) is [14] a conservative value based on multiple flush values for dP (0.45 kPa) for P-traps which was obtained in this study by extrapolation. This extrapolated value (0.45 kPa) was further confirmed by additional data which were obtained in a preliminary NBS laboratory study of the dP-Q_a-dH relationship in a 5-story stack. P-trap data relating dP and dH is presented in Figure 17.

Table 2. Levels of Peak Suction Producing a 25 mm (1.0 in) Trap Seal Reduction in WC-traps and P-traps for Single and Multiple Flushes

Test Procedure	Peak Suction Measurement (0.2s)			
	WC-trap vent (from Component Stack Data)		P-trap vent (from Townhouse Data)	
	kPa	(in W.G.)	kPa	(in W.G.)
Single flushes...............	1.00	(4.0)	0.62	(2.5)
Multiple (4) flushes.........	0.75	(3.0)	0.45	(1.8)

Table 3. SUMMARY OF PRINCIPAL RESULTS OF LABORATORY TESTS ON A FULL-SCALE TOWNHOUSE DRAINAGE SYSTEM WITH REDUCED-SIZE VENTS

Fixtures Discharged[a] (Active Traps)	TEST CONDITIONS						Number of Idle Traps
	Vent Terminals and Building Drain Open		Vent Terminals Closed and/or Building Drain Submerged				
	Additives (first and third runs)[b]	Idle Traps Failed After Four Runs Without Refill[c] (Cumulative dH)	Additives (all four runs)	Vents Closed	Drain Submerged	Idle Trap Failed After Four Runs Without Refill[c] (Cumulative dH)	
S3a.........	DET/fwdu in S3A.	0	fwdu in S3A.	Both..	No........	0	8
W5..........	None............	0	None........	Main..	No........	0	8
W2..........	PD in W2........	0	None........	Both..	No........	0	8
L1+W1.......	PD in W1........	0	None........	None..	Yes.......	0	7
B1+W1.......	None............	0	None........	Main..	No........	0	7
S3a+W1+W2...	DET/fwdu in S3A.	0	fwdu in S3A.	None..	Yes.......	0	6
C4+W1+W2....	None............	0	None........	Both..	No........	3	6
C4+W1+W2....	None............	0	None........	Both..	No........	3	6
C4+W1+W2....	DET in C4.......	0	None........	Sink..	No........	0	6
B1+W1+W2....	PD in W1........	0	None........	Both..	No........	0	6
B1+W1+W2....	BB in B1........	0	None........	None..	Yes.......	0	6
B1+W1+W2.....	BB in B1........	0	None........	Both..	Yes.......	2	6
S3a+W1+W2+W5	DET/fwdu in S3A.	0	fwdu in S3A.	Both..	No........	4	5
S3a+W1+W2+W5	fwdu in S3A.....	0	fwdu in S3A.	Both..	No........	5	5
S3a+W1+W2+W5	DET/fwdu in S3A.	0	fwdu in S3A.	Both..	No........	4	5

[a] S3A - fwdu compartment of a double bowl sink

S3B - non-fwdu compartment of a double bowl sink

W1, W2, W5 - water closets

L1, L2, L5 - lavatories

B1 - bathtub

[b] fwdu = food-waste-disposal-unit

DET = granulated detergent

BB = bubble bath

PD = paper diaper

[c] Reduced by 25 mm (1 inch from full-seal depth)

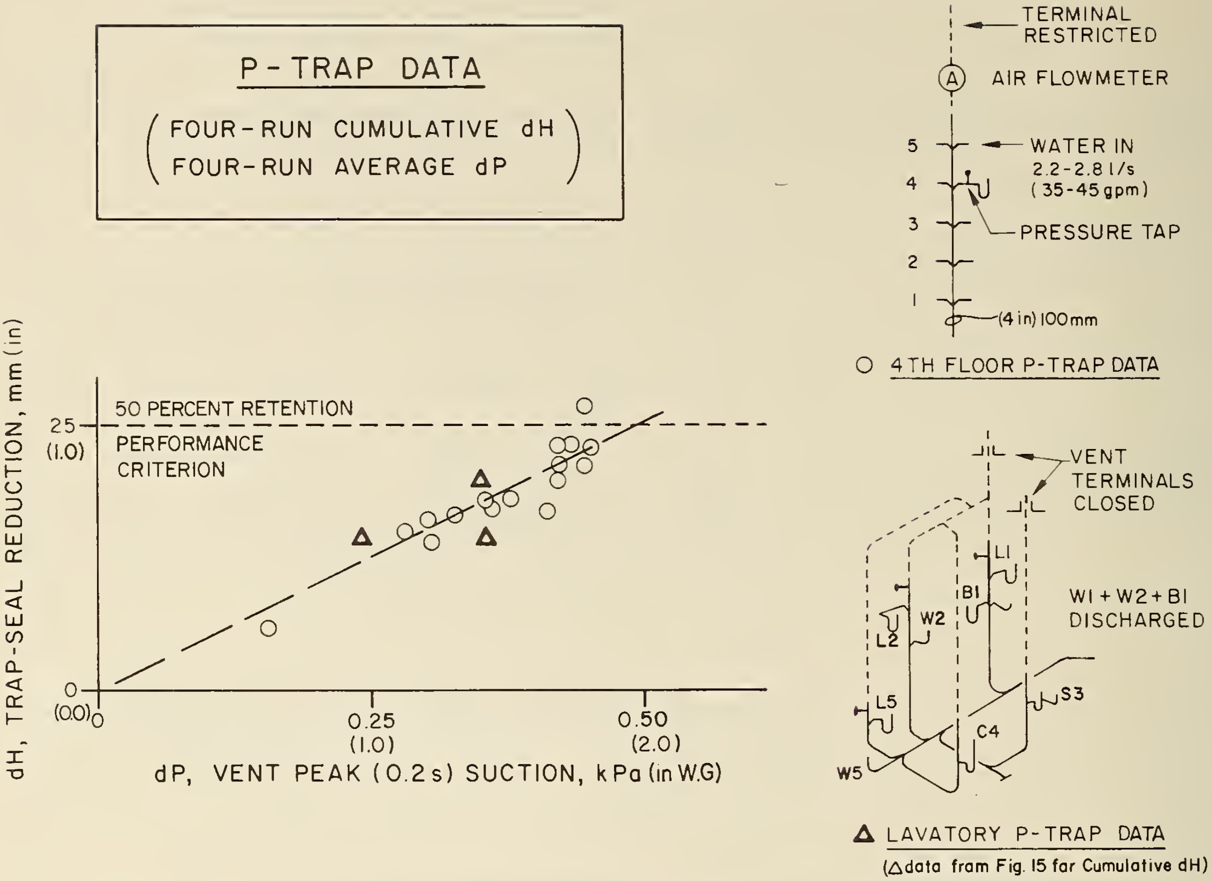


Figure 17. Comparison of P-Trap Data in Townhouse System and in 5-story Simple Stack for Multiple Flushes

The 5-story stack was intended to serve as a multistory counterpart to the "component stack" used in the study of short stacks in which the test conditions could be carefully controlled. The design of the experimentation for the 5-story, simple stack provided for the systematic addition/change of branch piping and fittings, so that the simple stack could serve as the core of a study of more complex systems. With varying water flow rate and variations in venting and fitting geometry, the pneumatic pressure fluctuations and trap-seal behavior could be studied under dynamic conditions. Results obtained in limited experimentation on the 5-story stack provide encouragement that with a suitable, expanded, test program such as that outlined in 4.1, a correlation for dynamic dP-Q_a-dH could be established for a range of designs, for systems of different heights.

The value of 0.375 kPa for design pressure drop has previously been recommended independently by Lillywhite and Wise [16] in connection with a procedure for sizing of stacks for single-stack drainage systems. Their recommendation for the equivalency of 25 mm (1 in) of trap-seal reduction and 0.375 kPa suction was based on practical experiments in multistory buildings up to 25 stories in which stack suction was compared with trap-seal reduction of English wash-down water closets [17].

3.4 APPLICATION OF FINDINGS FOR VENT SIZING CRITERIA FOR RESIDENTIAL SYSTEMS WITH SHORT STACKS, AND FIELD PERFORMANCE VALIDATION

The research described is performance oriented because data were obtained simultaneously relating the traditional specification type design criteria (pipe sizes based on specific air flow rates and peak suction levels) and a basic user need for protection of health through adequate trap-seal retention -- in the context of the performance framework described in Section 2. The findings indicated that the widely held assumption that a fluctuating suction of 0.25 kPa (1.0 in W.G.) is roughly equivalent to a trap-seal reduction of 25 mm (1.0 in) is erroneous. The data support a design pressure drop in the vents of 0.37 kPa (1.5 in W.G.) rather than the 0.25 kPa (1.0 in W.G.) on which the present codes are based. Utilization of these findings in the existing design criteria could result in a 50 percent increase in allowable dry vent pipe length, or a diameter reduction of about 8 percent, in all systems. Perhaps the most important result was the development of new criteria for 1-2 story systems that provide for vent size reduction of 1 to 4 commercial pipe sizes.

The RSV recommendations are presented in Table 4 and the sizing procedures and examples are given in detail in Appendix A (both from [14]). The selection parameters identified are: (1) vent function, (2) elevation of trap, and (3) the fixture unit load served by the vent. In the sizing sequence, the primary elements, or *fixture* vents are sized first. A fixture vent provides the primary or sole ventilation for a trap or group of traps located at the base of the vent. Where two or more fixture vents are connected, the joint

Table 4. *Recommended criteria for selecting dry-vent sizes for 1-2 story sanitary drainage systems*[a]

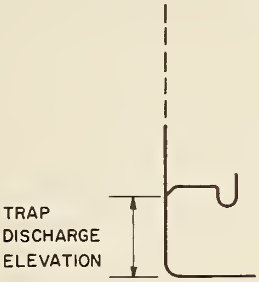
SIZING SEQUENCE	SELECTION CRITERIA			MINIMUM VENT SIZE (nominal pipe diameter)
	Function of vent	Elevation of trap[b] (determines distance of water fall)	Maximum load[c] (served by vent)	
First	[d] *FIXTURE VENTS:*	*ft*	*FU*	*in*
	Individual (serves single trap).	Up to 8	1 to 3	½.
			4 to 6	¾.
		8 to 16	1 to 3	¾.
			4 to 6	1.
	Common (serves two traps).	Up to 8	1 to 3	¾.
			4 to 6	1.
		8 to 16	1 to 6	1.
	Stack vent (Main vent at top of a soil or waste stack).	Up to 8	1 to 6	1.
			7 to 15	1¼.
			16 to 30	1½
		8 to 16	1 to 6	1¼.
			7 to 15	1½.
			16 to 30	2.
Next	[e] *CONFLUENT VENTS:*			
	For two fixture vents	Not applicable	Not applicable	One pipe size larger than the largest fixture vent served.
	For three fixture vents	Not applicable	Not applicable	[f] In most cases, increase one pipe size over largest fixture vent served.
	For four or more fixture vents.	Not applicable	Not applicable	[g] Area of pipe selected must equal or exceed the value computed from: $A_{CONFLUENT} = \sqrt{A_{LARGEST} \cdot \sum A_{SERVED}}$
Last	[h] *ARTERIAL VENT:*			
	Vent stack, or Stack vent serving as a relief vent	Not applicable	10	1¼ (36 ft max).
			10	1½ (120 ft max).
			30	1¼ (30 ft max).
			30	1½ (100 ft max).

Table 4, *Footnotes*

[a] This table may also be applied to 3-level split configurations in which the total height of water fall between the highest fixture and the main building drain does not exceed 16 ft.

[b] Elevation of trap above first lower (vented) horizontal fixture branch, (vented) soil or waste stack offset, or building drain branch that serves the trap.

Figure A



[c] Fixture unit values for usual plumbing fixtures found in residences[18]. For consistency, these values should be used for sizing the dry vents. The applicable code values, even if different from those given below, may be used for sizing the wet piping.

Common symbol	Fixture	Load
		FU
P-1	Tank WC	4
P-2	Lavatory	1
P-3	Bathtub	2
P-4	Shower	2
P-5	Sink w/fwdu and DWM	3
P-6	Clothes washer	3
F.D	Floor drain	3

[d] *Fixture vent:* Any single vent that provides the sole or primary ventilation for a trap or group of traps located at the base of the vent. These sizes are valid for vent lengths up to 25 ft. For longer lengths, increase by one pipe size.

[e] *Confluent vent:* A vent pipe that serves two or more fixture vents.

[f] Exceptions requiring two pipe size increase:

(Three) fixture vents served			Confluent vent
in	*in*	*in*	*in*
1	1	1	1½
1¼	1¼	1¼	2
¾	1	1¼	2
¾	1¼	1¼	2
1	1	1¼	2
1	1¼	1¼	2
1½	1½	1¼	3
1½	1½	1½	3

[g] Cross-sectional areas by which to calculate confluent vent size using the square-root formula are as follows:

Nominal diameter pipe	Internal cross-sectional areas		
	Schedule 40	Copper tube	
		M	DWV
in	*in*^{2}	*in*^{2}	*in*^{2}
½	0.304	0.254	
¾	0.533	0.517	
1	0.864	0.874	
1¼	1.495	....	1.317
1½	2.036	....	1.865
2	3.355	....	3.272
3	7.393	....	7.235

[h] These sizes (a one-pipe-size reduction derived from table 14 of [5]) are on the basis that significant pressure relief occurs through the building-drain and building-sewer route, significant circulation occurs in the branches of the vent network, and air demand is minimal in short stacks. If flooded sewer conditions are anticipated, the arterial vent size, obtained as indicated, should be increased one pipe size.

---

pipe is sized in the next step as a *confluent* vent by means of square-root formula which relates the sum of the areas of the fixture vents served to that of the confluent vent. Last in the sizing sequence is a consideration of the air circulation in the system as a whole. The *arterial* vent sizing criteria apply to DWV systems of more than one story and are intended to provide circulation and back-pressure relief. The criteria are meant to be supplemented by engineering judgment and close attention to details of installation. In a separate study based on an analysis of data in [12, 13, 14], Brownstein has made similar recommendations in the context of guidelines for plumbing designers on reduced-size vents for short-stack residential DWV systems [19].

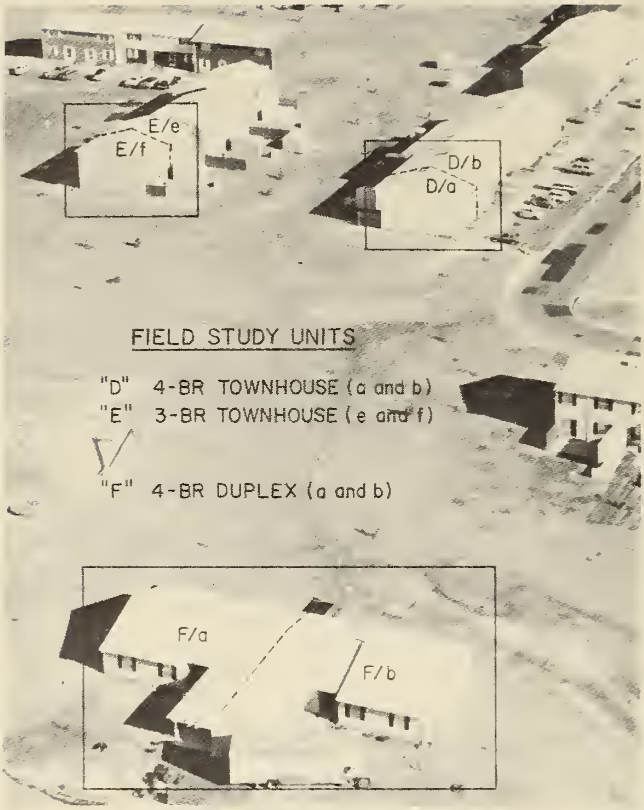


Photo 3.

Andrews Air Force Base
Field Test Houses,
Aerial View of D, E, and F
Units with Reduced-Size Vents
(Photo Courtesy Andrews Air Force Base)

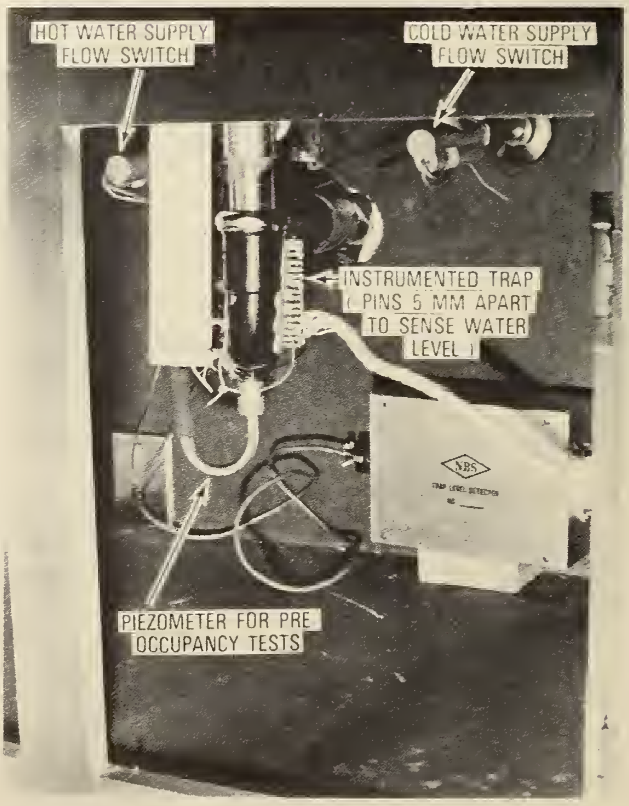


Photo 4.

Typical Lavatory Installation
with Instrumented
P-Trap and Water Supply Lines at
Andrews Air Force Base

To verify the utility of the laboratory findings in service, and to study the effect of service parameters such as frost closure of vents, natural loadings, and sewer pressure fluctuations, NBS has been carrying out a field study (to be reported separately). The criteria derived from the laboratory work were used in designing the vent systems for 3 types of homes: a 3-bedroom townhouse, a 4-bedroom townhouse, and a 4-bedroom duplex (See photo 3). Principal field measurements taken for study of reduced-size vent performance were the trap-seal retention (see photo 4) of P-traps and selected vent pressures near some of the selected traps.

In built systems, the performance intended (by the pressure-level-limit design criterion) is adequate trap-seal retention. This is more easily measured in built systems, following systematic testing guidelines, than pneumatic pressure excursion and peak air demand in the vent. Thus there is widespread interest in hydraulic test procedures for innovative systems involving measurement of trap-seal reduction. It has been recognized, however, that standardization of these procedures requires better information on service load patterns as a basis of test load selection [20].

The laboratory studies indicated that a cumulative 25-mm trap-seal reduction would not be likely unless the peak transient suction in the vent was on the order of 0.45 kPa. In the RSV field study, the test procedures utilized in the laboratory were adapated to the field in tests carried out before occupancy. The systematic test procedures of Figures 5 and 11 were followed. That a transient suction beyond 0.25 kPa (up to 0.45 kPa) does not cause a serious trap-seal reduction was confirmed in the field studies based on peak readings visually observed on magnetically-coupled pressure gages connected to selected vents. (Some tests were made with the vent terminal through the roof closed, in accordance with the test plan.)

In the field validation of the adequacy of laboratory-based design criteria for sizing RSV, an opportunity was provided for a pilot study involving measurement and data acquisition methods relating to water and energy usage. NBS provided sensing devices and an automatic data recording system which recorded the real time when triggered by a sensor. Several houses were instrumented with flow switches (to register on or off) on the hot and cold water supply lines to the fixtures, in conjunction with remote indicating devices on the house water meter, and on the watt-hour meter connected to the water heater. The principal objective of the pilot study was to develop measurement and data recording methods, although the data provided some definition of the time distribution of use at a number of water outlets.

Comprehensive data on water usage, as discussed in 4.2 is needed as a major building block of the performance approach, as it impacts on many areas of plumbing design, plumbing standards development, and test procedures utilized in laboratory research, especially as related to the design and evaluation of innovative approaches.

4. SUMMARY OF NEEDS TO IMPROVE PLUMBING MODELS THROUGH PERFORMANCE-ORIENTED RESEARCH

4.1 LABORATORY RESEARCH NEEDS FOR PLUMBING SYSTEMS

Traditional approaches to the evaluation of plumbing systems by current design criteria are not sufficiently flexible for evaluating innovative systems. In this paper we have broadly described, using the examination of the vent model as the basis of a simple example, the utility of performance methodology to extend traditional methods. We have also discussed the organization of existing knowledge into the performance (format) framework to maximize the utility of the available information to different groups of users and to reveal gaps in existing knowledge that suggest research needs.

The recent work shows that there is a significant opportunity to improve the precision and scope of experiments and plumbing design criteria for hydraulic (water supply and drainage) carrying capacity and for hydraulic load-producing effects of fixtures. This is possible because of recent state-of-the-art advances in instrumentation and data acquisition systems capable of making meaningful measurements of a number of the rapidly changing dynamic parameters typically occurring in a plumbing system at the same time. Statistical and mathematical techniques applied to such a data base would permit systematic and rational reduction of some of the large safety factors that have in the past been utilized to assure a safe level of performance in the absence of adequate analytical information.

A broad laboratory research program should be designed to take into account the interrelated areas of : I. Drain-Waste-Vent System Carrying Capacity, II. Hydraulic Load Imposed by the Fixtures, and III. Metrology of Plumbing Dynamics. Suggested principal research topics within a laborabory investigation to address hydraulic parameters in these areas are:

I. Drain-Waste-Vent System Carrying Capacity: A more definitive dynamic correlation of peak air flow demand, pneumatic pressure and the resulting trap-seal reductions from input Hydraulic Load as derived from II, taking into account the following field conditions:

A. Changes in direction (offsets, fittings)
B. Additives (solids, suds)
C. Soil or waste stack length (distance of water fall)
D. Changes in flow resistance (effective roughness factor) in service due to fouling and corrosion

I. Hydraulic Load Imposed by Fixtures: Better definition of the dynamic load of individual fixtures and combinations of fixtures for generation of a representative time-profile of hydraulic load as input to utilize in experimentation and computation in relation to I, taking into account:

A. Time distribution of discharge (time-profile) of single fixtures and combinations of fixtures
B. Attenuation of discharge rate as affected by geometry of branch piping connected to fixtures
C. Volume of water consumption of different fixtures
D. Peak and average flow rates and duration of flow

I. Metrology of Plumbing Dynamics: Better correlation between peak values measured and averaging period ("time-slice" width) used in data acquisition/analysis for I and II, needed as a contribution to a common base for:

A. Uniform, reproducible measurements among laboratories
B. Analysis and utilization of data for development of useful mathematical models, e.g., for trap-seal behavior and system capacity
C. Adapting the laboratory measurement approach to field data collection, and interpretation of field peak-value measurements

A specific benefit of improving the present method of expressing fixture loading effects by their hydraulic parameters in a common format for use in plumbing system design would be better correlation of the discharge vs. time-profile with system carrying capacity in terms of the allowable number of connected fixtures. If combined with documented data on frequency of use in service, as discussed in the next section, this would also contribute to improved precision of the fixture unit ratings assigned to the various fixtures and appliances. This improved precision would be reflected in reduction in the degree of overdesign of plumbing systems that is generally believed to exist with the traditional design criteria [21, 22].

4.2 FIELD RESEARCH NEEDS FOR IMPROVED PRECISION IN ESTIMATING PEAK HYDRAULIC LOADS AND ASSIGNING FIXTURE UNIT RATINGS

Although laboratory evaluation can define the hydraulic characteristics of fixtures and appliances i.e., duration of discharge "t", and flow rate, "q", the overriding research need is for field studies to define the time distribution of fixture operation during periods of maximum usage. From these data, updated values of "T", (average time between operations during peak use periods) could be derived for various fixtures in different occupancies. The three parameters, "t", "q", and "T" are utilized in the probabilistic calculation of loads and fixture unit ratings [10] for sizing water supply and DWV systems for buildings, see Figure 18.

Planning for the collection of usage data for interpretation in relation to hydraulic design (service loads) requires that sociological, seasonal, and geographic parameters be included in the program, and that data be obtained continuously over a substantial period of time for meaningful, statistically significant, interpretation of results, e.g. whether water is "saved" under a particular set of conditions, whether specific numerical changes in fixture-unit ratings can be recommended, etc. The feasibility and impact of such studies depends greatly on the development of prototype instrumentation and data collection suited to the scope and number of raw data measurements that should be recorded and analyzed.

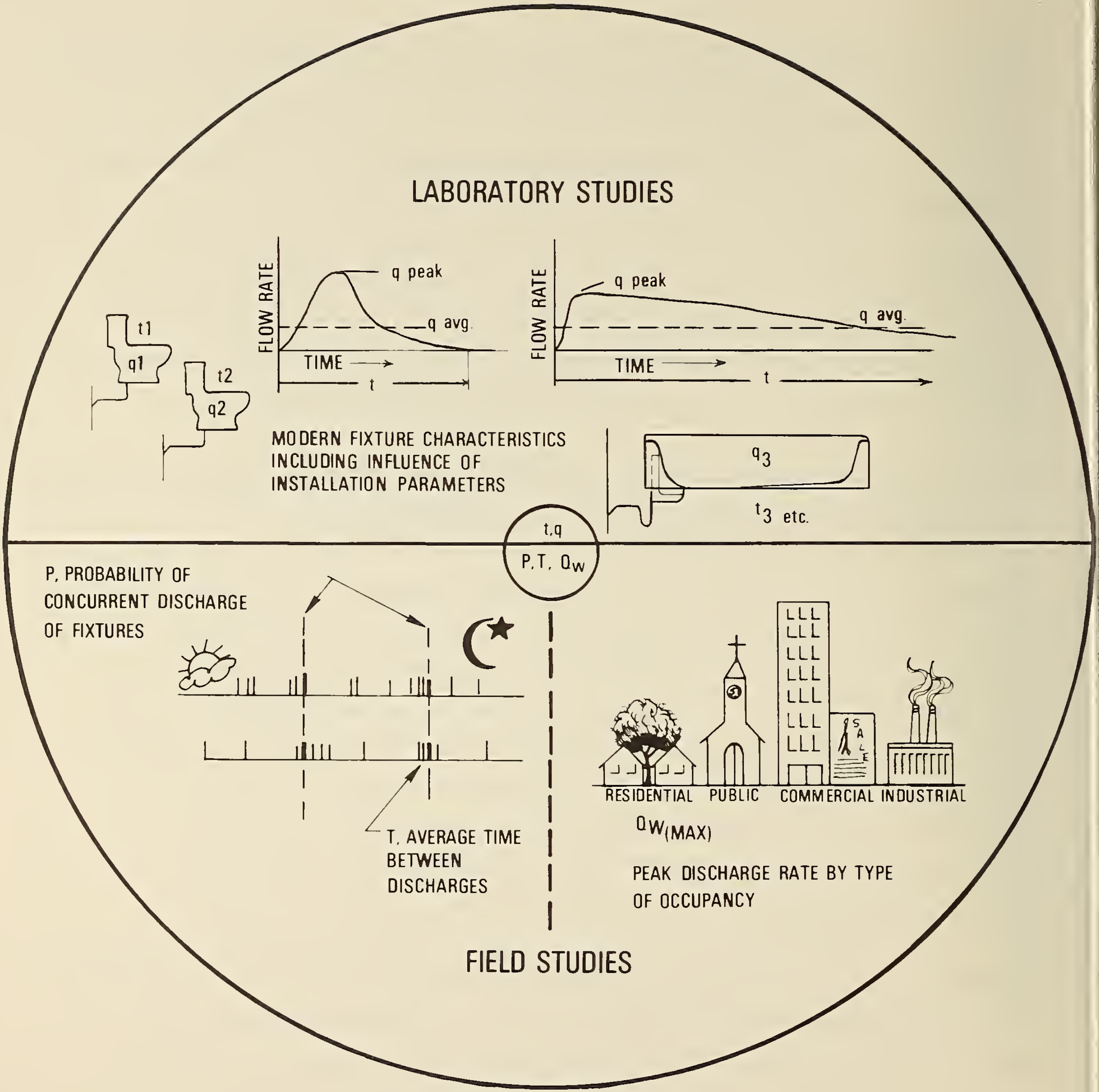


Figure 18. Principal Coordinated Inputs Needed to Update Hunter Curve for Drainage (a similar illustration could be constructed for Water Supply)

The pilot study described 3.4, emphasizing field measurement and data recording methods, is considered an initial step in the development of a uniform methodology of defining real-time usage patterns in plumbing systems. Such pilot studies are essential for the establishment of test methods that are viable under field conditions. Measurement procedures appropriate to the laboratory may be difficult to adapt to field conditions where solids and suds, as well as electrical disturbances caused by weather and a lack of control of flow conditions, add to the problem of keeping a total system operational and of remotely recording measurements that are meaningful [23, 24]. But some of these measurement system problems have to be addressed in the research if meaningful new criteria are to be developed to facilitate cost reduction, materials conservation, and water and energy conservation.

For example, knowledge of representative fixture use patterns in service is needed as the basis of an updated Hunter Curve and its associated Fixture Unit ratings. Updated definition of t, T, and q would provide a basis for improved precision of hydraulic load prediction (Q) for water distribution and drainage systems in buildings, for individual and on-site water supply and treatment systems, and for sewage treatment and disposal systems. This improved precision in load estimation is needed for the reduction of excessive safety factors in design, and for the realistic testing of innovative systems.

The Hunter Curve was derived from the binomial probability theory in such a fashion that it provides for any particular given system of one type of fixture, an estimated (design) peak discharge rate. The design rate is the greatest value of the two obtainable from the following criteria:

1. The rate which probably will occur, in the aggregate, in excess of 1 percent of the time by the smallest possible amount.

2. The rate which probably will be exceeded in the aggregate less than 1 percent of the time by the smallest possible amount.

To generalize the application of the theory, Hunter developed the "fixture unit concept" which provides a means of synthesizing the basic curves as described above into a single curve for estimating loads from typical systems comprising several types of fixtures, or "mixed" systems.

In recent times, engineers have metered the building water service on various occasions in limited studies to compare observed peak demand with that predicted from the Hunter Curve. Generally they have found the actual demand to be considerably less than that predicted from the Curve. However, there has been no work to systematically adjust the currently used values of the basic parameters of the Hunter model (t, T, q and the "fixture unit" ratings of the various fixture types) that determine the predicted hydraulic load (Q). Rather, only empirical modifications of the ordinate of the Curve have been suggested.

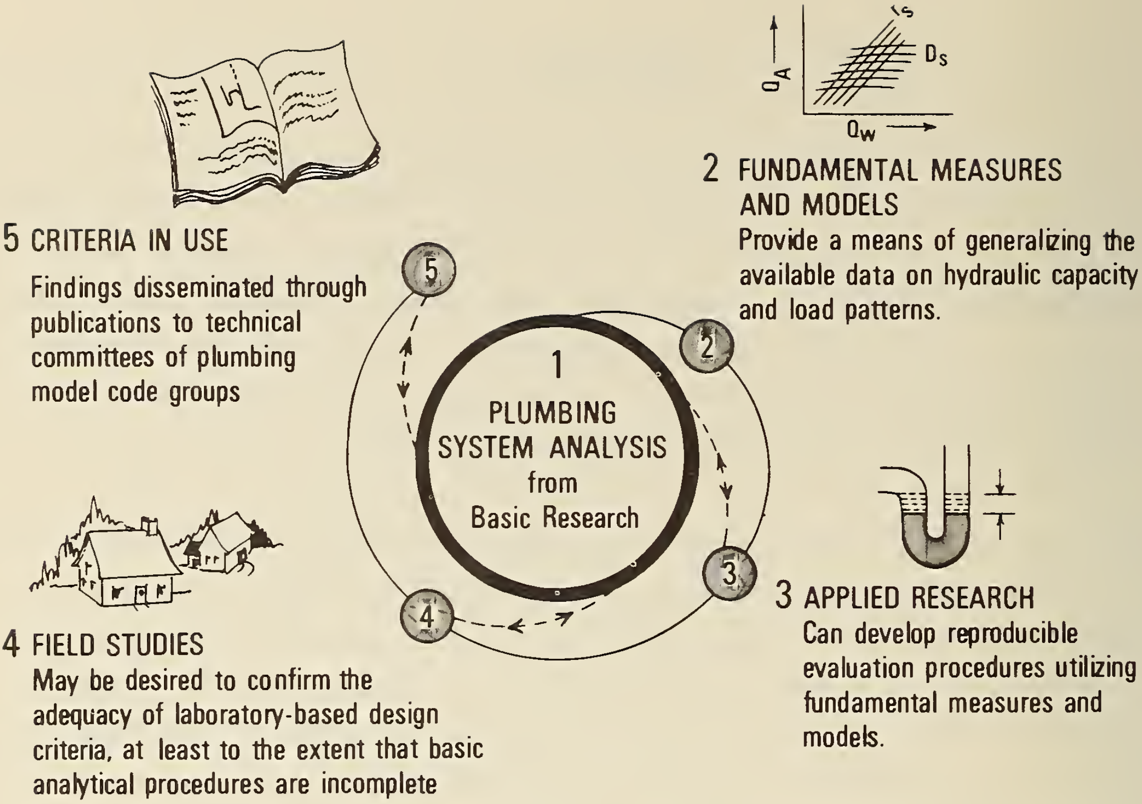
A long-range comprehensive national field program is needed. This work should use uniform, technically adequate methods of experimental design, data acquisition and analysis, and should involve all groups having a substantial interest in the subject of updating load prediction for plumbing systems (e.g. updating of the Hunter Curve).

5. CONCLUSIONS

The role of basic research in developing viable performance evaluations is depicted in Figure 19. This diagram illustrates the need for improved analytical capability that would permit both tentative design criteria and innovations based on such criteria to be evaluated directly in field studies or on the basis of reliable prediction (Figure 19, broken lines) of performance. Presently, the step-by-step procedure (Figure 19, solid line from 1 to 5) involves laboratory and field studies for validation.

However, research to strengthen the analytical capability, whether by computation or standard test method, would have significant impact on uniform and realistic procedures. For example, there is at present no standard method for determining and expressing the hydraulic characteristics of plumbing fixtures and their appliances, i.e., how much water a particular fixture uses or wastes, or what peak flow rate is generated, or the flush performance of water closets. This becomes of major concern to manufacturers and code officials in light of today's emphasis on energy and water conservation when legislation increasingly mandates the use of "water-conserving" fixtures [25]. In another example, there are no standard procedures for predicting long-term fouling effects under service conditions.

The scope of this paper has been concerned with what the performance approach is, concentrating on DWV hydraulic carrying capacity in the discussions, and with how performance methodology could be utilized in the evaluation of innovative plumbing systems. Comprehensive performance evaluation of plumbing systems on the basis of function, efficiency, and economy requires not only adequate knowledge of hydraulic carrying capacities and the characteristic patterns of service hydraulic loads as has been described, but also requires better definition of parameters that affect durability and maintainability under service conditions. In some cases, the system evaluation requires interdisciplinary interaction such as for evaluation of (the installed system) fire safety. Whether combustible piping material is fire-safe depends on the plumbing and other building systems considered together, as installed.



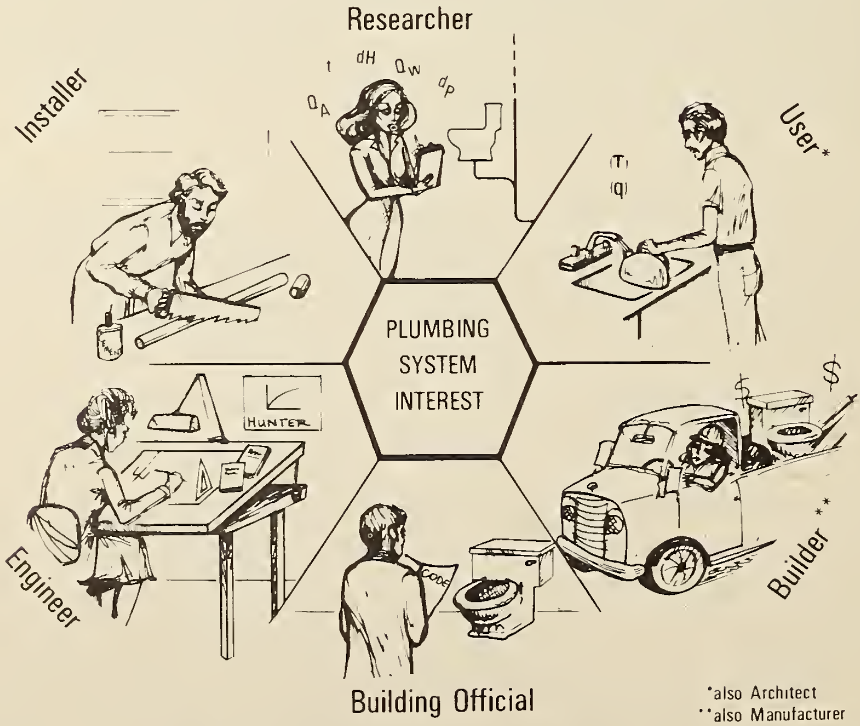
2 FUNDAMENTAL MEASURES AND MODELS
Provide a means of generalizing the available data on hydraulic capacity and load patterns.

5 CRITERIA IN USE
Findings disseminated through publications to technical committees of plumbing model code groups

3 APPLIED RESEARCH
Can develop reproducible evaluation procedures utilizing fundamental measures and models.

4 FIELD STUDIES
May be desired to confirm the adequacy of laboratory-based design criteria, at least to the extent that basic analytical procedures are incomplete

Figure 19. Model for the Development of Performance Criteria



*also Architect
**also Manufacturer

Figure 20. Schematic Indicating Groups Representing Cross-Section of Interests in Plumbing System Specifications

Broad evaluation of the installed system should also be based on knowledge of the psychological needs of the users of plumbing systems, in addition to the technical parameters. For example, the unwanted sound generated by the plumbing system (apart from functional capability) impacts daily on the user's living activities if the noise is excessive. Study in the area of behavioral sciences in relation to building technology has long been neglected and is only now beginning to receive recognition as an important part (to the user) of performance evaluations [26]. The assignment of responsibility for development and implementation of interdisciplinary criteria is not specifically delineated at the present time, so these criteria tend to be neglected.

Evaluation of plumbing systems on the basis of performance would in the long term enable innovative designs to be evaluated on their performance in terms of user needs (and on this basis enter the marketplace). The present need to systematically develop uniform criteria for design and evaluation of innovation in plumbing has been recognized nationally in the ANSI A40 (committee) project, Minimum Requirements for Plumbing [27]. An A40 subcommittee has recently undertaken the drafting of a performance standard for plumbing as a means of classifying and evaluating the 'performance attributes of interest' and the 'limit states of concern'. This effort could serve as a starting point for plumbing system interests to evolve the uniform design and evaluation methods. Figure 20 is a schematic of the groups representing the cross-section of interests which could ultimately benefit from improved plumbing system and design evaluation criteria, and installation specifications.

Drawing again from the work of Fenves and Wright [1], the following quote seems to describe what a broadened base of plumbing specifications (broadened to include performance methods) is intended to accomplish:

> "The quality of the built environment, including its functionality and safety, is directly dependent on the quality of the specifications controlling the design. Ventre [28] has argued that because of the 'diverse, dispersed, detached, and discontinuous' nature of

> the building industry, specifications, and especially their legal embodiments in the codes, represent essentially the only 'collective memory' of the industry."

And finally, the performance approach, then is not a sweeping replacement of existing codes, but something to be assimulated within this 'collective memory' that can be used as a complementary methodology to aid code administrators in evaluating innovative designs. The performance approach also seeks to put information in a systematic format for easier access by (possibly adaptable to computer retrieval by) the different groups of users involved. With systematic test methods and evaluation procedures which can be uniformly used and enforced, performance evaluation and design methods can provide a needed supplement to traditional prescriptive methods.

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Appendix A. Sizing Reduced-Size Vents, Procedure and Examples

A.1. General Approach

It is recommended that the piping schematic first be marked with applicable fixture unit ratings by fixture. The sizing sequence, using table 4, is:

STEP 1—Fixture vents
STEP 2—Confluent vents
STEP 3—Arterial vent

It is important to identify on the DWV piping schematic the various vent types given in table 4. A *fixture* vent is a vent pipe that provides the sole or primary ventilation for a trap or group of traps located at the base of the vent. A *confluent* vent is a vent pipe that serves two or more fixture vents. The fixture vents need not all join the confluent vent at a single point. That is, confluent vents should be sized on the basis of the fixture vents served, not on the basis of the branch vents that may connect directly to the confluent vent. For example, figure A.1 shows that Confluent Vent 2 serves Fixture Vents 1, 2, and 3 which do not all connect at the same point.

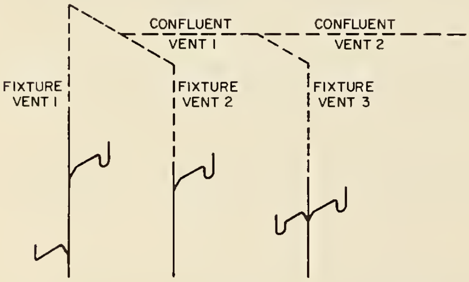


Figure A.1 *Schematic showing fixture and confluent vents.*

The *arterial vent* (applicable only to systems greater than one story) may be recognized as the main artery of the vent system serving other vents and as the most direct route for the relief of potential back pressure in the building drain.

A.2. Example of Use of Table 4 to Size RSV

Sample calculations of how the vents in the townhouse system were sized, step-by-step, are as follows:

STEP 1—Fixture vents. The appropriate fixture-unit loads for single fixtures were obtained from the National Standard Plumbing Code [18], for the fixtures in the townhouse system, as listed in footnote c of table 4. From this, the connected fixture-unit load by stack was determined as listed in table A.1 for the five stacks. From the geometry of the system however, W5 was considered to be vented equally through stacks 4 and 5. On this basis, the FU loads vented by these two stacks were recalculated as listed in table A.2.

Table A.1. *Connected fixture-unit load by stack*

Stack designation	Fixtures	Load
		FU
1	L1+W1+B1	7
2	L2+W2	5
3	S3	3
4	C4	3
5	L5+W5	5

Table A.2. *Estimated fixture-unit loads vented through stacks 4 and 5*

Stack designation	Fixtures	Load
		FU
4	C4+½W5	5
5	½W5+L5	3

The results of the determination of the FU loads for the five stacks are shown in figure A.2. Fixture-unit loads considered to be *vented* through each stack are shown, rather than the loads *connected*. The DWV vent piping is standard size to 6 in above the fixture flood-rim level.

To complete *STEP 1*, the early tentative criteria [13] now incorporated in table 4) were utilized to size the fixture dry vents for stacks 1–5. This produced the sizes shown in table A.3.

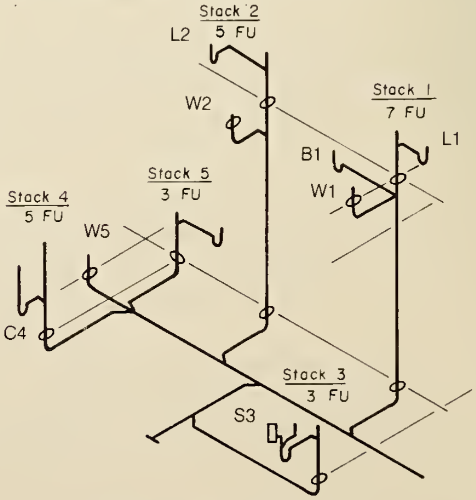


Figure A.2 *Schematic showing Fixture Unit loads vented through each stack.*

Table A.3 *Fixture dry vent sizes for townhouse system*

Stack designation	Selection Criteria			Nominal pipe size
	Fixture vent type	Elevation of trap(s)	Load	
		ft	*FU*	*in*
1	Stack vent....	8 to 16.......	7	1½
2	Stack vent....	8 to 16.......	5	1¼
3	Individual....	Up to 8......	3	½
4	Common.....	Up to 8......	5	1
5	Common....	Up to 8......	3	¾

STEP 2—Confluent vents. As an aid to the computation of sizes for confluent vents, figure A.3 was prepared showing, not only the sizes for the fixture dry vents, but also the unsized elements X, Y, and Z, (the vent header). The sizes for these elements were determined by computation using the square-root relationship given in table 4, and selecting the next larger pipe size from footnote g of table 4. The relationship is:

$$A_{CONFLUENT} = \sqrt{A_{LARGEST} \cdot \sum A_{SERVED}} \quad \text{(A.1)}$$

where

$A_{CONFLUENT}$ = theoretical internal cross-sectional area required in the confluent vent

$A_{LARGEST}$ = actual internal cross-sectional area for the largest fixture vent served by the confluent vent

$\sum A_{SERVED}$ = sum of actual internal cross-sectional areas of all the fixture vents served by the confluent vent

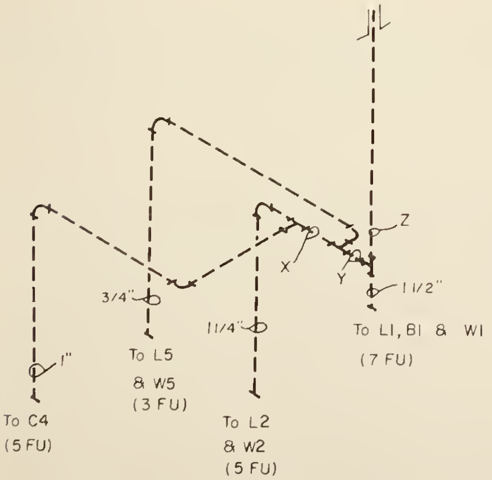


Figure A.3 *Schematic showing four fixture vents and three confluent vents (X, Y, and Z) for the townhouse system.*

Sizing confluent vents by eq (A.1) results in a one-pipe-size increase for all cases where two fixture vents (from ½ to 2 in) are served. Where three fixture vents (any combination of three of ½ to 2 in) are served, eq (A.1) produces eight exceptions to a one-pipe-size increase. These require a two-pipe-size increase over the largest fixture vent served and are listed as footnote f of table 4. For confluent vents serving four or more fixture vents, the confluent vent size should always be calculated by use of eq (A.1).

Confluent vent sizing of X, Y, and Z, the elements of the vent header of the townhouse system, is tabulated in table A.4. This completes *STEP 2*.

Table A.4 *Confluent vent sizes for townhouse system*

Confluent vent	Nominal sizes of fixture vents served	Nominal size confluent vent	
	in		*in*
X	1, 1¼..........	Increase one size........	1½
Y	1, 1¼, ¾.......	Increase two sizes....... (see table 4, f)	2
Z	1, 1¼, ¾, 1½....	Use eq (A.1) area and select nearest larger commercial size...... (See table 4, g)	2

STEP 3—Arterial vent. Utilization of these sizing criteria to provide a pressure relief route for the building drain may take precedence over the sizes calculated for this route in *STEP 1* or *STEP 2*. For the NBS experimental townhouse system, the arterial vent was chosen as Stack 1. The FU load on the system was 23 FU, and a flooded sewer was not made a condition, thereby making the arterial vent size, 1½ in. This size was already the size of Stack 1 by *STEP 1*; the vent terminal size was 2 in by *STEP 2*. Thus no size change was called for to meet the 1½ size determined in *STEP 3*.

When the final vent sizes are determined as just described, a DWV piping schematic should be marked to complete the procedure.

A.3 Construction Note

Familiarity with the RSV sizing procedures and the rationale behind them is needed when they are applied to the on-site as-built wet piping configuration. This can be particularly important because construction constraints and other field conditions may result in on-site changes in the planned wet system that would require significant modifications in the planned sizing of the reduced-size dry vents.

Appendix B - Definitions

1. Arterial vent - A vent in DWV systems of more than one story, intended to provide circulation and back-pressure relief in multi-story systems.

2. Attributes - The overall characteristics the occupant desires for his living unit (in this paper, Sound, Durable, Safe, and Functionally Effective).

3. Averaging period - Time period selected for measurement for which the (data acquisition system used in the townhouse investigation) computer would retain a single value representing an average value of the many values scanned for that (time) period.

4. Confluent vent - A vent pipe that serves two or more fixture vents.

5. Criterion - Some physical or chemical characteristic or property that is subject to measurement and that can be used as a meaningful *quantitative* measure or indicator of adequacy in the satisfaction of a (performance) Requirement.

6. dH - The amount of decrease in trap-seal depth from full-seal depth.

7. dP - Maximum value of vent suction obtained during a run for a selected averaging period (see also "averaging period").

8. Elements - The interrelated built parts of the living unit (in this paper, major categories are the building, its systems (of which plumbing is one), and their subsystems).

9. Emissions - Blowback of water or gas into occupied spaces due to positive pressure.

10. Evaluation - A systematic procedure or standard test method for determining if a Criterion has been met.

11. Fixture vent - Any single vent pipe that provides the sole or primary ventilation for a trap or a group of traps located in the proximity of the base of the vent.

12. Performance (approach) - An approach to design and evaluation that centers on the idea that the performance of products, devices, systems, or services can be systematically described and measured in terms of user Requirements without regard to their particular combination of physical and chemical characteristics, their design, or the method of their construction. In this paper, the view is taken that a structure and its environment together furnish a living unit with certain overall Attributes desired by the user (see also Attributes). The living unit in turn is comprised of built Elements (see also Elements) which can be systematically related to the Attributes by (performance) Requirements (see also Requirements).

13. Q_a - Maximum value of air demand flow rate obtained during a run for a selected averaging period (see also, "averaging period").

14. Requirement - A *qualitative* statement of basic user needs.

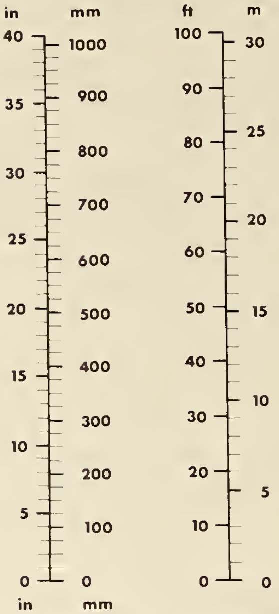
15. Time profile - The change in magnitude of a hydraulic parameter for a time period on the order of 10 to 300 seconds. For this study, some data smoothing was achieved by means of a data collection system which averaged instantaneous values to a single value for a (pre-selected) "averaging period" on the order of a fraction of a second (the response time of a trap-seal) (See also "averaging period").

16. Units, abbreviations (see also Appendix C) -

cm	centimeter
ft	foot, or feet
gpm	gallons per minute
kPa	kiloPascal (see Pascal)
l,ℓ	liter
m	meter
min	minute
Pa	Pascal, = Newton per square meter, by definition
psi	pounds per square inch
s	second
W.G.	Water Gage

Appendix C, Units and Conversion Factors

LENGTH



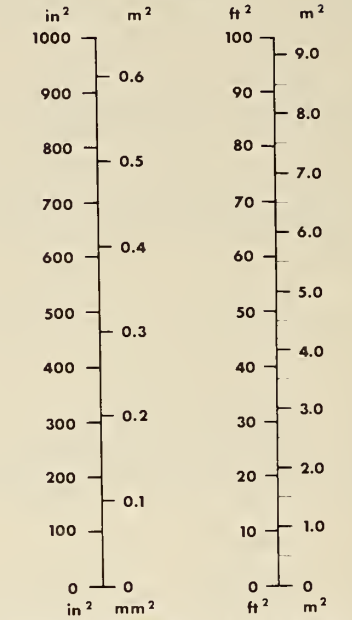
1 in = 25.4 mm

0.0394 in = 1 mm

1 ft = 0.305 m

3.281 ft = 1m

AREA



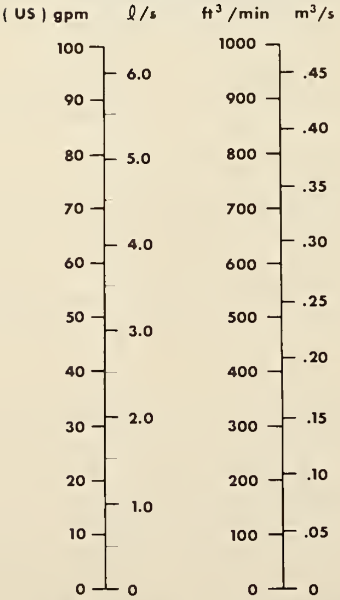
1 in² = 6.451 × 10-4 m²

1536.098 in² = 1 m²

1 ft² = 9.290304 × 10-2 m²

10.763910 ft² = 1 m²

VOLUME FLOW RATE



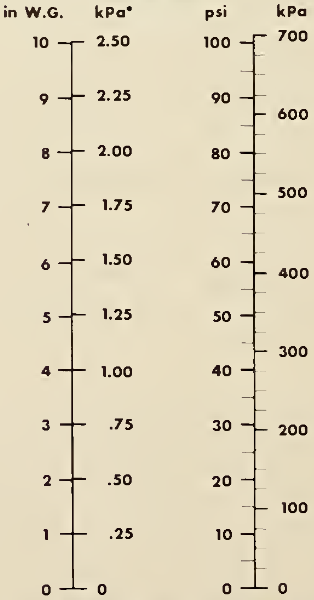
1 (US) gpm=6.309 × 10^{-2} liters/s

15.85 (US) gpm =1 liters/s

1 ft³/min=4.719474 × 10^{-4} m³/s

2118.9 ft³/min=1 m³/s

PRESSURE



1 in W.G.=0.2488 kPa

4.02 in W.G.=1 kPa

1 psi=6.895 kPa

0.145 psi=1 kPa

* k = times 1000
Pa = Newton / meter² (N/m²), by definition

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

An overview is presented indicating how the performance approach to plumbing system design can be used to extend traditional methods to innovative systems. Identification of the plumbing performance needed in a built system is used to classify current design criteria intended to furnish this level of performance. Some current design criteria may provide a higher level of performance than is actually needed by the user. In other cases, no standard test method, criterion, or evaluation technique exists. Puttin existing knowledge into a performance format increases the utility of this knowledge and facilitates identification of needed research to fill the gaps. Some of the mathematical models now used for system design and pipe sizing in plumbing codes are reviewed in the context of performance-oriented research. The results of experimental work in plumbing systems with reduced-size vents (smaller than allowed by codes) are presented as an example of the use of the performance approach, and illustrate a case where performance criteria permit relaxing of vent design practice. Conceivably the re-examination by plumbing designers of traditional design criteria against measured user needs could be beneficially extended to other areas of plumbing design such as water distribution, storm drainage, and plumbing fixtures. Beyond this, it has been recognize that uniform guidelines for evaluation of innovative systems, based on research findings, are essential for wide acceptance of performance methods, particularly by the regulatory community.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Performance; plumbing systems; reduced-size venting.

18. AVAILABILITY ☒ Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☒ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 ☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED 20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	21. NO. OF PAGES 61 22. Price

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