# A framework for the implementation and design of pilot-scale distribution systems

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## ABSTRACT

In recent years, model distribution systems have become valuable tools for understanding physical, chemical and microbiological processes that occur in full-scale distribution systems. These systems enable numerous treatment strategies to be examined in controlled conditions and without adversely affecting the water quality at a customer's tap. Many model reactors have been developed for obtaining water quality data for evaluating very specific processes that occur in the distribution system (e.g. trihalomethane formation). The simulated distribution system (SDS) test is used to predict the formation of trihalomethanes in the distribution system, annular reactors (AR) are commonly used for biofilm studies and pipe rig systems can be used for a variety of studies including corrosion and biofilm. Of the three model reactors, pipe rig systems provide the most flexibility, however relatively few standard or *de facto* testing procedures have been developed in comparison to the other laboratory-based model systems (e.g. SDS test protocol). There are several hydraulic configurations that can be modelled along with various lengths and diameters of different pipe materials. However, this flexibility and the lack of standard pipe rig designs cause difficulties in making broad comparisons among research projects. This paper outlines the important design variables of a pipe rig system and provides examples of different options for each variable. Based on a thorough review of previous pipe rig studies, a framework was developed to assist in the design and selection of pipe rig configurations. It is recommended that the framework provides a method for selecting the physical and hydraulic configuration for future pipe rig investigations. Ultimately, the framework would provide the water industry with potential designs that would allow for improvement in data evaluation and strategies for minimizing water quality degradation in distribution systems.

**Key words** | biofilm, corrosion, distribution systems, pipe loop

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## INTRODUCTION

The water industry has become increasingly aware of the deleterious effects distribution systems can have on water quality. Performing full-scale water distribution system studies can be costly and may only provide limited or case-specific information. Furthermore, full-scale trial runs may result in negative impacts on the system's water quality or pose the potential to increase health risks to consumers. Since it is critical to evaluate the acute and long-term impact that treatment strategies may have on water quality and pipe materials in distribution systems, many experimental or model reactors have been designed for modelling distribution systems.

Model reactors have been developed to allow greater control in operational (e.g. flow rate) and environmental (e.g. temperature) parameters common to distribution systems, which is not possible for most full-scale situations. Several basic designs of model distribution systems are summarized in Table 1. To that end, model reactors have been used for evaluating nutrients affecting bacterial regrowth (Camper, 1996; Ellis *et al.*, 2000; Gagnon *et al.*,

**Table 1** | Summary of model distribution systems

| Model | Potential applications | Limitations |
|---|---|---|
| SDS test | THM formation potential (Koch *et al.* 1991) | • No flow<br>• Limited to formation potential |
| Immersed corrosion test | Corrosion rates (ASTM G31-72 1972) | • No flow |
| ARs | Corrosion rates and biofilm studies (Volk *et al.* 2000) | • Larger surface area to volume ratio than found in pipes<br>• Limited information on correlation of results between ARs and pipe rigs<br>• Cannot study actual pipe sections |
| Pipe rigs | Corrosion, metal release, biofilm | • Size<br>• Very few standard rigs |

2000), treatment impacts on microbiological regrowth (LeChevallier *et al.*, 1998), disinfection strategies, corrosion control strategies (LeChevallier *et al.*, 1993; MacQuarrie *et al.*, 1997; Rompré *et al.*, 1997) and the impact of pipe materials on water quality (Van Andel, 2001). Although chemical reactions, such as trihalomethane formation in a distribution system, can be approximated with a simulated distribution system (SDS) test (Koch *et al.*, 1991; Summers *et al.*, 1996) this test is limited in that it does not consider factors such as hydrodynamics, or the impact of biofilm growth. Therefore, other types of reactor systems that evaluate the combined effects of shear stress, stagnant flows and other hydraulic changes with the impact of disinfection, corrosion and microbial regrowth are widely used to assess the impact of treatment decisions.

Annular reactors (ARs) (e.g. Characklis, 1988) and Propella reactors (e.g. Parent *et al.*, 1996) are the most commonly used biofilm reactors for modelling water quality in a distribution system at a bench-scale level. Although other column reactors have been developed for biofilm studies (e.g. Rittmann *et al.*, 1986; van der Kooij *et al.*, 1995), ARs and Propella reactors have become the standard biofilm reactors for the water industry by *de facto*. Both of these reactors are completely mixed reactors, which allow for *in situ* sampling and analysis of accumulated biofilm. The principle of operation is that water flows through an annular gap, which is mixed by an inner rotating drum (Characklis, 1988). Shear stress is controlled by the rotational speed of the inner drum and hydraulic retention time is controlled independently by the volumetric flow rate. These types of reactors have been used as generic biofilm reactors to evaluate biofilm processes (Peyton & Characklis, 1993) and are widely used in the water industry to model microbial processes in distribution systems (Camper, 1996; Gagnon & Huck, 2001). Recently, Sharp *et al.* (2001) developed a protocol for assessing biological stability in distribution systems. In addition to biofilm studies, several studies (Rompré *et al.*, 1997; Volk *et al.*, 2000) used ARs for developing corrosion control strategies and to assess microbially-influenced corrosion in distribution systems.

One of the advantages of ARs and the Propella reactor is that they are hydraulically simple to use and the results

can be easily compared among studies. However Camper (1996) observed that the number of biofilm HPCs was approximately 10 times greater in the AR (1994 model; BioSurface Technologies Corp.) than in a 100-mm pipe rig. This observation could be partially explained by a larger specific surface area in the AR ($270 \, \mathrm{m}^{-1}$) than in the pipe loop ($40 \, \mathrm{m}^{-1}$), for a resulting specific surface ratio of approximately 7 to 1 (Gagnon & Huck, 1997). In addition to this issue, ARs introduce Taylor vortices, which will result in biofilm or side deposits that are tapered across the biofilm coupon (Gjaltema et al., 1994). While these can be overcome by examining trends in biofilm production/inactivation, it is often necessary to conduct pipe rig studies to provide a closer representation of treatment decisions on distributed water quality.

A pipe rig system is a very good tool for simulating water distribution systems. They are able to simulate hydraulic conditions and actual pipe material and provide insight to water quality, corrosion rate and microbial conditions within a pipe. Pipe rig configurations and operating conditions vary greatly and there are very few standard designs. At the same time, the wide array of pipe rig design variables provides considerable flexibility in design and operation.

The objective of this paper is to develop a framework for designing pipe rig or pilot-scale level distribution systems. To achieve this objective, the paper reviews existing designs and approaches for modelling water quality in distribution systems. This review provides a rationale for selecting the appropriate scale of model distribution systems; ultimately, it is the goal of this review to establish criteria for selecting pipe rig design variables.

## PIPE RIG SYSTEMS

Assessing the impacts of internal corrosion on water distribution systems, at full-scale, can be a challenge for utilities because evaluating the physical condition of the distribution system is hindered by the inability to examine the system without excavating it (Levin & Schock, 1991). Still, it is important to be able to observe how various strategies may impact the distribution system. This can be

achieved using a model distribution system. Pipe rigs are the more commonly used reactor for corrosion studies. Several pipe rigs have been developed to simulate water distribution systems, while others have been used to simulate plumbing within a building (Levin & Schock, 1991). Pipe rig systems can be used alone or in conjunction with coupon tests or coupled with pilot plant investigations. The advantages of using a pipe rig are that the variables affecting corrosion can be systematically controlled and evaluated, and alternate conditions can be tested simultaneously under comparable conditions. Pipe rig tests can be used to provide data on many variables including material selection, corrosion rates, effects of fluctuations or modifications of water quality, or alternative treatments. The practical methodologies for studying corrosion with pipe rigs can be carried over to other water distribution studies, such as microbiological regrowth, biofilm analysis and other water quality problems. Furthermore pipe rigs can be designed to evaluate water quality in pipe mains (McMath et al., 1997), dead ends or non-flow periods (Lytle & Schock, 1996), household connections (Kirmeyer et al., 1994) or a combination of these levels of scale (MacQuarrie et al., 1997).

The terminology used for pipe rig systems varies in the literature; some designs are referred to as pipe rigs while others are referred to as pipe racks or pipe loops. Using the term pipe loop implies a system that has some form of recirculation or long sections of pipe that may be coiled to resemble a loop. Not all pipe rig systems are set up to recirculate and some rigs do not physically resemble loops; therefore, to avoid confusion in this paper, the term *pipe rig* will refer to all systems that incorporate some form of pipe section to simulate distribution systems. The term pipe loop will be limited to cases in which water is recirculated in the experimental system.

### Pipe rig set-up

Pipe rig system set-ups can vary greatly between studies, because there are many different design variables which are dependent on the individual project objectives. In particular, some of the common design variables are pipe material, flow configuration, flow velocity and pipe length

(Table 2). The following section will discuss the variables that can affect the results of a study and highlight some of the advantages and disadvantages of some of the popular standard pipe rigs.

### Test section style—permanent or pipe inserts

The most important component of a pipe rig is the test section. It is here where all reactions with the water and pipe will occur. Depending on the study objectives, test sections can either be permanent pipe (Maddison *et al.*, 2001) or temporary pipe inserts that are periodically removed for analysis (Neden *et al.*, 1992). For permanent pipe sections, lengths can vary from 1.5 m (5 ft) (Maddison *et al.*, 2001) to 25.6 m (84 ft) (MacQuarrie *et al.*, 1997); however pipe rigs having a total system length of 1.3 km have also been used (McMath *et al.*, 1997). In general, the length of the test section is highly dependent on the study objectives. Once-through pipe rigs, for example, will often employ a longer test section to increase contact time in the reactor. Temporary pipe inserts are much shorter in length, so that they can be handled more easily. In many cases, they must be shipped to other laboratories for analysis. Pipe inserts are usually no longer than 0.3 m (1 ft) (LeChevallier *et al.*, 1990). However, the amount of sample volume required for monitoring water quality parameters (e.g. pH, metals) should be considered to establish minimum total volumes for pipe rigs and the potential dispersive effects during sampling (AWWARF, 1990).

Pipe rigs can incorporate both the longer permanent sections in series with pipe insert sections (MacQuarrie *et al.*, 1997), although not all pipe rigs use pipe inserts to obtain *in situ* samples. Cast iron studs have been used as coupons at the entrance and exit of a permanent pipe section (Holden *et al.*, 1995; Camper, 1996). Using a combination of permanent pipe sections in conjunction with pipe inserts provides an opportunity to collect a variety of water quality data.

It is important that the pipe material used in a pipe rig is representative of the material used in the full-scale water distribution system. Common materials used in pipe rig investigations are cast iron (Maddison *et al.*, 2001), ductile iron (Neden *et al.*, 1992), mild steel (Reiber, 1993),

asbestos-cement piping (Buelow *et al.*, 1980) and PVC (LeChevallier *et al.*, 1990). The use of actual pipe sampled from the distribution system can be useful because the results may be more representative than if new pipe is used, although this may limit the scope of the study to the distribution system from which the pipe section was sampled. The use of new pipes is also important, since corrosion mechanisms differ between new and old pipes. In most cases, 100 mm (4 in) cast-iron mains are usually used because they provide an average size that is representative of most areas of a distribution system (Camper, 1996). Also, 100-mm pipe provides adequate interior pipe surface that enables chemical and microbiological surface reactions to occur.

Corrosion control studies are often investigating the effects of metal release in residential plumbing. In that case, it is common to use copper tubing with intermittent joints that have 50/50 lead/tin solder and a diameter of 12.7 mm ($\frac{1}{2}$ in) (Yannoni & Clovellone, 1998). Other materials such as PVC are used in conjunction with copper to observe the effects of biofilm inactivation with various disinfectants (LeChevallier *et al.*, 1990).

### Pipe rig flow configuration

Pipe rig systems can be designed either for water to flow through once, or to be recirculated (Table 2). The flow-through configuration provides a more realistic model, since most distribution systems and household plumbing are flow-through. For this reason, pipe rigs are constructed more often as flow-through. However, recirculating pipe rig systems provide a useful approach to equilibrium conditions for studies concerned with solubility of corrosion by-products or inhibitor mechanisms (Levin & Schock, 1991). Recirculating pipe loops also allow uniform water quality conditions to be established throughout bulk water in the reactor. Variation in pipe diameter and pipe material may occur in a recirculating system. However, the specific impact that these physical parameters would have on bulk water quality conditions would be difficult to discern from a single pipe rig, as a recirculating system is essentially a completely mixed reactor (CMR). Accordingly, the bulk water quality conditions are assumed to be uniform through the reactor,

which can be a significant advantage for examining chemical or microbial kinetics in a distribution system.

Although flow-through rigs provide an experimental reactor that is more representative of a full-scale system (i.e. plug-flow behaviour), one drawback that Maddison *et al.* (2001) found was that appreciable changes in water quality are small if there is insufficient contact time between the pipe and the bulk water. This is particularly important for pipe rig studies that are interested in evaluating chemical or microbial processes, which may have long reaction rates. Consequently, a 1.3 km long pipe rig used by McMath *et al.* (1997), which had a retention time of 48 h, was designed to use representative velocities and to obtain meaningful contact times to allow sufficient time for water quality to degrade.

A recirculating system has the benefit of providing a much longer retention time, while maintaining recirculating flow rates indicative of actual distribution systems. A high recycle rate allows for the recirculating system to be modelled as a CMR (Camper, 1996). The retention time in a recirculating system is independent of the recirculating rate or the velocity through the pipe section, whereas, with a once-through system, the retention time is a function of the pipe velocity and flow. With a flow-through configuration, the velocity is controlled by the flow into and out of the test section and the diameter of the section. By increasing or decreasing the velocity, the retention time changes accordingly. With a recirculating flow configuration, the velocity in the pipe section is controlled by the recirculation flow, which is not the same as the influent feed flow. Therefore hydraulic retention time (HRT) in a recirculating flow configuration is independent of the velocity and is adjusted by increasing or decreasing the influent feed flow rate; which is consistent with the benefits of having shear stress and HRT as independent parameters in bench-scale systems (e.g. annular reactor).

Retention times may be limited to a maximum value, depending on the system set-up, thus leading to a degradation of water quality. Haudidier *et al.* (1989) connected six recirculation loops in series, such that each loop had a retention time of 40 h/loop, resulting in a system retention time of 240 h or 10 days. Using a recirculation system consisting of an old cast-iron test section, Lohmann *et al.* (1997) found that a retention time longer than 1.4 days

(Table 2) resulted in low levels of dissolved oxygen and chlorine and high concentrations of turbidity and iron. Lohmann *et al.* (1997) indicated that the degradation in water quality resulted from the unusual environmental factors that were imparted from the age of the water.

The recirculating flow configuration increases the complexity of a pipe rig system by incorporating a recirculation pump. There are two ways of recirculating the water using the pump (Figure 1). One approach is to have an entirely enclosed loop (Lohmann *et al.*, 1997; Eisnor *et al.*, 2001). Another method includes a reservoir that will act as an equalization basin. The recirculation pump draws from the reservoir while the pipe section drains into it (Reiber, 1993; Camper, 1996). The disadvantage of the reservoir is that it will have its own residence time during which time water quality may change, due to stagnation in the basin or settling of suspended material. This can be minimized if the residence time of the reservoir is designed to be a fraction of the pipe rig's residence time. However, depending on the goals of the study, the reservoir can ensure stable water quality and prevent excessive build-up of corrosion products (Reiber, 1993).

## Flow velocities and stagnation

Velocity, or the lack of it, is known to affect corrosion in water distribution systems (Schock, 1999). A common velocity used when simulating water distribution systems is 0.3 m/s (1 fps) (Reiber, 1993; McAnally & Kumaraswamy, 1994; MacKoul *et al.*, 1995; Camper, 1996). However, studies that are attempting to simulate residential plumbing typically desire lower flow rates, but since residential pipes are typically 12.7 mm ($\frac{1}{2}''$) diameter, the velocity is higher than that experienced in a 100 mm (4'') main (MacQuarrie *et al.*, 1997).

Several studies incorporate periods of stagnant flow (e.g. MacKoul *et al.*, 1995; MacQuarrie *et al.*, 1997), which simulate conditions along dead-end sections of water distribution systems, as well as conditions experienced in household plumbing during periods of no water use (i.e. during the night). In most cases, stagnation time varied depending on the study. However, it was common to have periods of 4 h on then 4 h off, in an attempt to simulate residential plumbing flow conditions (Mackoul *et al.*, 1995;

**Table 2** | Operational summary of various pipe rig studies

| Purpose | Config. | Corrosion measurement | Stag. time | Pipe length | Pipe diameter | Pipe material | Duration | Velocity | Author |
|---|---|---|---|---|---|---|---|---|---|
| Corrosion control | Recirc. | Chemical | n.r. | 3.2 m | 100 mm | Old cast iron | 24 months | n.r.[1] | Lohmann et al. 1997 |
| Corrosion control | Flow-through | Chemical | Varied | n.r. | n.r. | Lead, copper & lead/tin solder | 6 months | 0.3 m/s | MacKoul et al. 1995 |
| Corrosion control | Flow-through | Chemical | Varied | 1.5 m | 100 mm | Old cast iron | 12 months | 0.06 m/s | Maddison et al. 2001 |
| Corrosion control | Flow-through | Chemical | 8 h | 9.1 m | 12.5 mm | Lead, copper & lead/tin solder | 12 months | n.r. | Yannoni & Clovellone 1998 |
| Corrosion control | Flow-through | Weight loss, electrochemical & chemical | Varied | 25.6 m & Inserts | 12.5 & 25 mm | Cast iron, lead, copper & lead/tin solder | 12 months | 0.45 & 0.79 m/s | MacQuarrie et al. 1997 |
| Corrosion control | Flow-through | Weight loss, electrochemical & chemical | Varied | 25.6 m & Inserts | 12.5 & 25 mm | Cast iron, lead, copper & lead/tin solder | 12 months | 0.45 & 0.79 m/s | Churchill et al. 2000 |
| Corrosion control | Flow-through | Weight loss & chemical | Varied | 25.6 & Inserts | 12.5 to 25 mm | PVC, lead, copper & lead/tin solder | 12 months | 0.45 & 0.79 m/s | Kirmeyer et al. 1994 |
| Corrosion control | Flow-through | Weight loss & chemical | Varied | 67 m & inserts | 12.5 mm | Copper & lead/tin solder | 18 months | 0.5 m/s. | Treweek et al. 1985 |
| Corrosion control | Flow-through | Chemical | n.r. | n.r. | n.r. | Lead and copper | 6 months | n.r. | Cantor et al. 2000 |
| Corrosion control | Flow-through | Weight loss | 8 & 68 h | Inserts | 75 mm | Copper & lead/tin solder | 7 months | 0.3 m/s | McAnally & Kumaraswamy 1994 |
| Corrosion control | Flow-through | Chemical | 22 & 72 h | Coupons | 12.5 mm | Brass, copper, zinc & lead | 30 months | 0.36 m/sr. | Lytle & Schock 1996 |

**Table 2** | Continued

| Purpose | Config. | Corrosion measurement | Stag. time | Pipe length | Pipe diameter | Pipe material | Duration | Velocity | Author |
|---|---|---|---|---|---|---|---|---|---|
| Corrosion control | Flow-through | Chemical & microbial | n.r. | 30 m | 150 mm | Old cast-iron | 12 months | 0.3 m/s | Clement et al. 2002 |
| Corrosion | Recirc. | Chemical | 12 h | n.r. | n.r. | Old cast iron | n.r. | n.r. | Price & Jefferson 1997 |
| Corrosion | Recirc. | Weight loss | n.r. | Coupons | n.r. | Mild steel, copper, brass, solder coating | 3–4 months | 0.03 m/s | Reiber 1993 |
| Corrosion | Recirc | Chemical | Varied | 1.2 m | 12.5 mm | Copper | n.r. | 0.36 m/s | Schock et al. 1995 |
| Biofilm & corrosion control | Flow-through | Electrochemical | n.r. | 11 m | 12.5 mm | Black iron | n.r. | 0.04 m/s | LeChevallier et al. 1993 |
| Biofilm & corrosion | Flow-through | Electrochemical | n.r. | 22 m | 12.5 mm | Iron, galvanized, copper, PVC | n.r. | 0.04 m/s | LeChevallier et al. 1990 |
| Biofilm & corrosion | Flow-through | Weight loss | n.r. | 3 m | 75 mm | Old cast iron | n.r. | n.r. | Holden et al. 1995 |
| Biofilm | Flow-through | n.r. | n.r. | 0.15 m | 100 mm | PVC, ductile iron & old cast iron | ongoing | n.r. | Neden et al. 1992 |
| Biofilm | Flow-through | n.r. | n.r. | 1300 m | 110 mm | Not stated | n.r. | 0.01 m/s | McMath et al. 1997 |
| Biofilm | Recirc. | n.r. | n.r. | 31 m/loop2 | 100 mm | Cement-lined cast iron | n.r. | 1 m/s | Haudidier et al. 1989 |
| Biofilm | Recirc. | n.r. | n.r. | 0.6 m | 100 mm | Mild steel | n.r. | 0.3 m/s | Camper 1996 |

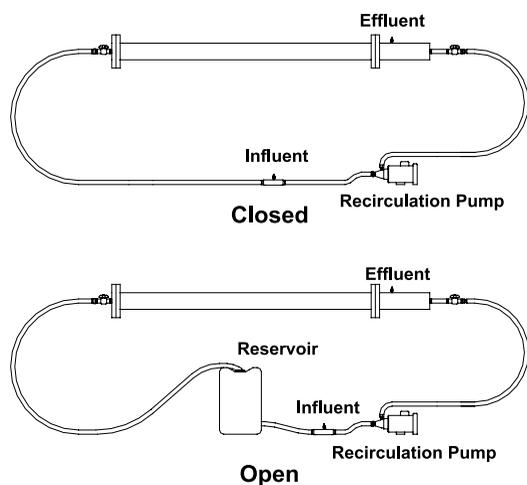[1]n.r.=not reported.
[2]Six loops in series.

**Figure 1** | Open pipe loop versus closed pipe loop.

Churchill *et al.*, 2000). Studies that have incorporated stagnation into their experimental design have noted that the effect of water stagnation on corrosion and microbiological processes is complex and is highly dependent on the pipe material, disinfectant decay, water chemistry and temperature of the pipe rig. Lytle & Schock (2000) found that metal levels rapidly increased with respect to stagnation time. However after the oxidant concentration was depleted, the lead concentration began to stabilize and the copper concentration exhibited a lower concentration.

## Pipe rig site location and duration

The total duration of the pipe rig study must be determined by the time required to maintain stable metal, microbiological, and/or water quality levels, and the number of samples required to achieve a desired accuracy and confidence in the data result (Sandvig, 1995). Typical durations of studies range from 6 months to 2 yr (Mackoul *et al.*, 1995; Lohmann *et al.*, 1997).

Choosing the site for the pipe rig pilot plant must be carefully considered. Ideally, the pipe rig system should be sited within existing facilities (Lohmann *et al.*, 1997; Maddison *et al.*, 2001), but if not, it should be easily accessible and close to a water source. Aside from water treatment plants, pipe rigs have been built and operated at

laboratories (LeChevallier *et al.*, 1993), throughout a water distribution system (Neden *et al.*, 1992) or at a dedicated test site (McMath *et al.*, 1997).

## Measurement of corrosion and water quality parameters

Corrosion can be measured by three general methods (Levin & Schock, 1991). Specimen exposure testing involves extended exposure of the material, followed by physical and chemical examination and weight-loss measurement (McAnally & Kumaraswamy, 1994). Electrochemical measurement permits 'instantaneous' measurement of corrosion rates by electrical resistance measurement, linear polarization and galvanic method (MacQuarrie *et al.*, 1997). Electrochemical measurement is very good for measuring uniform corrosion, but does not always provide adequate information on irregular corrosion. Chemical analysis includes an evaluation of changes in levels of corrosion by-products (Price & Jefferson, 1997).

Parameters other than corrosion rates can be measured during a pipe rig study. Bulk water quality parameters such as disinfectant residual, pH, dissolved oxygen, alkalinity, hardness, turbidity and colour are a few examples. In addition, it is common for studies to monitor metal concentrations such as lead, copper and iron. In corrosion control studies, concentrations of corrosion inhibitors (such as polyphosphate) can also be measured (Maddison *et al.*, 2001). Studies that look at microbiological regrowth and biofilm analysis will test for common microbiological assay, such as heterotrophic plate counts (HPC), total cell counts and total coliform counts (e.g. LeChevallier *et al.*, 1998). Microbiological samples are taken from either the bulk liquid or from the biofilm attached to either the pipe surface (e.g. Donlan & Pipes, 1988), a pipe insert (LeChevallier *et al.*, 1990) or pipe coupon (Haudidier *et al.*, 1989).

Data analysis and reporting from a pipe loop study are also important for decision makers to make informed process changes to maintain water quality in distribution systems. Wysock *et al.* (1995) showed that lead and copper data resulting from pipe rig studies might not follow a

normal distribution. It was therefore recommended that non-parametric tests (i.e. Wilcoxon signed rank test) would be more appropriate for data analysis. Similarly, Camper (1996) used log-transformed data for statistically analysing microbiological counts. Finally, sample replication within pipe rigs and frequency is critical for pipe rig studies. Several studies have developed protocols for estimating the minimum number of samples to be taken in a pipe rig study (Kirmeyer *et al.*, 1994; Wysock *et al.*, 1995). Sample replication becomes a greater issue for old test materials (e.g. Clement *et al.*, 2002) as variability of pipe scale and redox will be greater.

## Standardized pipe loop systems

In order to make it easier to perform a pipe rig study, several research groups have designed standard pipe rigs. These rigs were designed for specific purposes and generally serve those functions well. Three standard pipe rigs are: the Illinois State Water Survey Machined Nipple Test (ISWS) (ASTM Standard 2688, Method C; Reiber *et al.*, 1988), the Army Construction Engineering Research Laboratory (CERL) Pipe Loop (Prakash *et al.*, 1988) and the American Water Works Association Research Foundation (AWWARF) Pipe Loop (AWWARF, 1990). All three of these rigs are designed for flow-through studies.

The ISWS machined nipple test is based on ASTM Standard D2688 Method C. It consists of a short length of pipe in a PVC sleeve that is directly connected to the pipe system being tested. Its main advantage is the specimen holder is designed so that flow conditions within the test section reproduce the effect of pipe hydrodynamics. An improved version of the ISWS incorporates more pipe inserts, facilitates the use of actual pipe sections without needing to machine the outside of the nipple and simplifies the hardware. The ISWS can be incorporated into other pipe rigs to further complement a study. MacQuarrie *et al.* (1997) used the ISWS in conjunction with online corrosion monitoring equipment and copper tubing test sections.

The CERL Pipe Loop is constructed of PVC and incorporates both flat coupons and pipe inserts. It can be used to make a comparison of actual corrosion on pipe surfaces, comparisons of multiple samples of the same type of coupon and comparisons of several different kinds of materials. An advantage of the CERL Pipe Loop is that the rig is very compact and is orientated vertically, to minimize the amount of suspended matter deposited on the exposed surface.

The AWWARF Pipe Loop was designed to be simple in design, easily constructed, reasonably priced, applicable to both large and small systems and flexible in application. One of the driving forces behind its design was the USEPA's drinking water regulation for lead and copper. The rig is constructed of PVC except for the test sections. It can incorporate multiple test sections, which permits the evaluation of more than one type of material and can include a CERL Pipe Loop, as well as three pipe test loops. Based on data and experience from six water utilities, Kirmeyer *et al.* (1994) developed a standard protocol for operating and constructing the AWWARF Pipe Loop. In the studies reviewed, the AWWARF Pipe Loop was popular for corrosion control studies (MacKoul *et al.*, 1995; Yannoni & Clovellone, 1998; Sorg *et al.*, 1999; Cantor *et al.*, 2000). However the basis for design of these pipe rigs was to establish a framework that could be used to evaluate specific objectives, such as testing for compliance with lead and copper regulations. Since their inception, variations from the standard pipe rigs have occurred to study other test objectives (e.g. biofilm formation) thus creating inconsistencies in experimental design, which may make data comparison more difficult.

## IMPLEMENTING A PIPE RIG STUDY

Given the magnitude of design variables and the lack of consistency in the literature for pipe rigs, the selection of pipe loops represents a significant challenge to researchers. Consequently, designing and operating a successful pipe rig system requires proper planning, which would be assisted through the development of a design framework. The most important pieces of information that are needed from the beginning are clear and specific objectives, such that development of the experimental plan and pilot plant design can proceed.
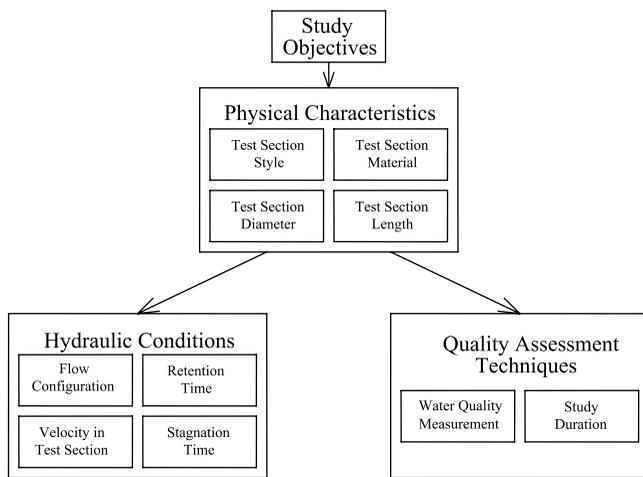
**Figure 2** | Pipe-rig design framework based on three general distribution system characteristics.

The purpose of this section is to present a clear and understandable rationale that can be used to select suitable design variables for pipe rig design. The described criteria are based on previous studies and are meant to be used as a framework to assist in selecting an optimal design based on the study's objectives.

## Study objective

Establishing the study objective should be the first step in designing a pipe rig. Without a clear objective, certain features may be incorporated into pipe rigs that are unnecessary or detrimental to the overall objective. In addition, important design variables may be overlooked.

## Key design variables

Figure 2 outlines the design variables that need to be considered when designing a pipe rig. These variables can be divided into three categories: the physical characteristics of the test sections, the hydraulic conditions of the pipe rig and quality assessment techniques. The categories are arranged in a hierarchy, such that the physical characteristics should be established prior to choosing the hydraulic conditions or the quality assessment techniques.

Tables 3 to 5 outline the choices for each design variable, provide some information that will assist in the selection of each option and offer examples of possible study objectives and applications that each option is suited to. The example objectives are only a few of the many possible applications that pipe rigs can be used for. The goal is to be able to take the study objective or application that is established and go through each section in order and match up the suitable pipe rig design variables.

Many of the design variables are related to one another and this is shown as the typical corequisite in the tables for each variable. Often, two design variables are related to one another if one of the design variables is set to a certain value or choice; as such, it typically dictates what the corresponding design value will have to be set at. For example, the selection of copper pipe as the test material will likely require that pipe diameters to be approximately 12.7 mm, which is typical of copper tubing used in residential plumbing.

## Physical characteristics

### Test section style

The test section can either be a permanent pipe section or pipe inserts/coupons (Table 3). Pipe rigs also have the flexibility to incorporate both permanent sections and pipe inserts or coupons. The test section style that is chosen may dictate the pipe length that is selected. Pipe inserts or coupons are usually very short ($<0.30$ m), so that they are easy to handle and analyse when inserted or removed. The test section style may also dictate the form of corrosion measurement. Permanent pipe sections are not suitable for corrosion rate determination using weight loss measures, while pipe inserts are not suitable for chemical corrosion measures, unless an adequate retention time is established. An adequate retention time can be achieved by having many pipe inserts in series, incorporating a recirculating flow regime or having stagnation time.

Permanent pipe sections are suitable for most objectives, as long as the previously mentioned considerations are accounted for. Pipe inserts or coupons are ideal for any study where the interior of the pipe needs to be examined, such as scale analysis or biofilm studies.

## Test section material

When selecting a test material, it is important to pick one that is representative of the system that is being simulated. Common test section materials are cast-iron (old or new), copper (with and without lead/tin solder), and PVC (Table 3). Material selection can easily be dictated by the study objectives. Studies simulating water distribution systems should typically use old cast-iron, asbestos-cement pipe or PVC, while studies concerned with corrosion of household plumbing should use copper tubing, with lead/tin soldered joints at regular intervals.

Pipe rigs that incorporate cast-iron surfaces will often involve new or aged pipes from existing full-scale systems. The advantage of using old cast-iron pipes is that the results may be able to be applied directly to the full-scale system that the pipes were sampled from. The disadvantage is that results are very site specific, as the observed changes in water quality are highly related to the specific corrosion by-products on the pipe. One must also consider possible disruption of redox conditions of the outer scale layers, and disruption in scale integrity. Studies have shown considerable re-equilibrium time might be needed, and that replication of sections of even a single long length of pipe is inexplicably not necessarily good (Clement et al., 2002). Furthermore, combining dissimilar metals in a pipe rig may result in galvanic corrosion, unless the metals are properly separated. However, depending on the study objectives, this form of corrosion may be an important part of the pipe rig.

Although PVC pipe does not corrode, this pipe material is common in some water distribution systems and will experience biofilm formation. Therefore, many studies observing biofilms and distribution system regrowth will have a test section using PVC.

## Test section diameter

There are typically two common diameters that are used in pipe rig studies (Table 3): 12.7 mm ($\frac{1}{2}''$) and 100 mm (4″), although other sizes are acceptable to use. Typically, if 12.7 mm tubing is used, the material is copper and part of the study objective is to simulate residential plumbing systems; however, if 100 mm pipe is used, it is either

cast-iron or PVC and part of the study objective is to simulate water distribution systems. If aged pipe material is used, it should be noted that the original diameter would most likely be less than the actual diameter of the pipe when it is removed from the ground, due to years of corrosion product build-up.

## Test section length

The test section length may be limited by several factors. The first factor is related to budget constraints; the longer the pipe section, the higher the cost. Also, for old-cast iron pipes, section length may be dictated by how much old pipe a utility has in storage or how much they are willing to dig out of the ground for the study. Another issue is the amount of space available. Large diameter pipes will take up a great deal of space if they are very long. This is not as much of a problem for copper tubing, because it is pliable and long lengths can be formed into a small convenient coil.

Assuming unlimited budgets and space, the different options for test section length are shown in Table 3: short, medium and long. Short test sections are typically pipe inserts or coupons and are usually less than 0.3 m long. These can be coupled together to form a longer test section, if necessary. Medium test sections are in the range of 1 to 3 m long. With test sections this long it may be wise to incorporate either a recirculating flow configuration or periods of stagnation to increase the retention time. Long test sections are those in excess of 10 m. Most long test sections incorporate a flow-through configuration.

It is important that with long pipe sections, the retention time is adequate enough to ensure that a difference between influent and effluent water quality can be observed. This may have to be achieved by adjusting the velocity for a flow-through configuration.

## Hydraulic conditions

### Pipe rig flow configuration

The pipe rig flow configuration can either be flow-through or recirculating (Table 4). In general, flow-through is cheaper and easier to operate than a recirculating system.

**Table 3** | Physical characteristics design options

| Design option | Typical corequisite | Applications/study objectives | Design considerations |
|---|---|---|---|
| **Test section style** | | | |
| Permanent pipe | • Test section Length > 1.0 m | • Most applications and objectives | • Not suitable for corrosion rate determination using weight loss measures |
| Pipe inserts/coupons | • Test Section Length < 0.3 m | • Biofilm/regrowth studies<br>• Corrosion scale analysis studies | • Easy to remove inserts for scale and biofilm analysis<br>• Several sections can be placed in series to increase overall length and retention time<br>• Not suitable for corrosion rate determination using chemical measures unless retention time >1 h |
| **Test section material** | | | |
| Cast-iron—old | • Pipe diameter≈100 mm<br>• Pipe Length >1 m | • Studies simulating water distribution systems<br>• Corrosion control studies<br>• Impact of disinfectants on corrosion<br>• Biofilm/distribution system regrowth studies<br>• Corrosion scale analysis studies<br>• Iron release studies | • Provides good insight of what may happen in a real distribution system with old cast-iron pipes<br>• Old pipes may be hard to come by<br>• Focused on objectives dealing with water distribution system<br>• Possible disruption in redox conditions of the outer scale layer and disruption in scale integrity |
| Cast-iron—new | • Pipe diameter≈100 mm<br>• Pipe length >1 m | • Studies simulating water distribution systems<br>• Corrosion control studies<br>• Impact of disinfectants on corrosion<br>• Biofilm/distribution system regrowth studies<br>• Corrosion scale analysis studies<br>• Iron release studies | • The use of new cast-iron pipes is not common in literature |
| Copper with lead/tin solder | • Pipe diameter > 25 mm<br>• Pipe length > 9 m<br>• Stagnation | • Studies simulating residential plumbing<br>• Copper and lead release studies<br>• Corrosion control studies | • Necessary for simulating residential plumbing and metal concentrations at consumer's tap<br>• Copper and lead corrosion is gaining importance with the USEPA's Lead and Copper Rule |
| PVC | | • Distribution system regrowth studies | • No purpose for corrosion studies |

**Table 3** │ Continued

| Design option | Typical corequisite | Applications/study objectives | Design considerations |
|---|---|---|---|
| **Test section diameter** | | | |
| Tubing 12.7 mm | • Copper tubing<br>• Flow-through configuration<br>• Pipe length > 5 m | • Studies simulating residential plumbing<br>• Copper and lead release studies<br>• Corrosion control studies | • Most likely will incorporate stagnation times<br>• Connect lengths of copper tubing together with lead/tin solder |
| Pipe 100 mm | • Cast-iron, PVC<br>• Flow-through or recirculation configuration<br>• Velocity 0.3 m/s or less | • Studies simulating water distribution systems<br>• Corrosion control studies<br>• Impact of disinfectants on corrosion<br>• Biofilm/distribution system regrowth studies<br>• Corrosion scale analysis studies<br>• Iron release studies | • Pipe is usually heavy and will require a proper stand<br>• Old cast-iron – original diameter > diameter at time of study |
| **Test section length** | | | |
| Short: < 0.3 m | • Inserts | • Biofilm/distribution system regrowth studies<br>• Corrosion studies with weight loss measures<br>• Corrosion scale analysis studies | • Have a viable means to mount the pipe inserts/coupons<br>• Consideration of sample volume should be given |
| Medium: 1.0 m–3 m | • Recirculating or flow-through with stagnation | • Studies simulating water distribution systems<br>• Corrosion control studies<br>• Impact of disinfectants on corrosion<br>• Corrosion scale analysis studies<br>• Iron release studies | • May require a recirculating flow configuration or stagnation times to achieve adequate retention time |
| Long: > 10 m | • Flow-through | • Metal release studies | • Costly and difficult with cast-iron and PVC<br>• Ideal for copper since long lengths can be coiled<br>• Pipe rig site must be large enough |

**Table 4** | Hydraulic conditions options

| Design option | Typical corequisite | Applications/study objectives | Design considerations |
|---|---|---|---|
| **Flow configuration** | | | |
| Flow-through | • Velocity & pipe length = set so that adequate retention time is achieved | • Corrosion and metal release studies that have stagnation time<br>• Long term corrosion rate through weight loss measures<br>• Corrosion scale studies<br>• Corrosion in residential plumbing | • With flow-through it is important to have a large retention time > 1 h<br>• Stagnation is one way of achieving this |
| Recirculation | • No stagnation | • Metal release studies<br>• Biofilm and regrowth studies<br>• Impact of disinfectants on corrosion | • Allows for long retention times with short test sections<br>• Complicated hydraulic issues |
| **Retention time** | | | |
| Very short | • High velocity<br>• Short pipe | • Studies using electrochemical and weight loss corrosion measures | • Only good for long term weight loss and electrochemical measures of corrosion |
| Medium | • Recirculating flow configuration<br>• Long stagnation times | • Metal release studies | • Ideal for observing conditions in a water distribution system since water age can be that old |
| Long: > 36 h | • Recirculating flow configuration<br>• Long stagnation times | • Metal release studies | • Water quality will degrade to represent extremities of a distribution system<br>• Depletion of dissolved oxygen and/or disinfectant residual can significantly alter the amount and form of metal release |
| **Velocity in test section** | | | |
| Stagnant | • Flow-through configuration | • Studies simulating on/off flow conditions in household plumbing<br>• Metal release studies | • Different stagnation configurations<br>• Extra on/off valves |
| Low: < 0.01 m/s | • 100 mm cast-iron | • Studies simulating low flow conditions in water distribution systems | • Low velocities will increase retention in flow-through configuration |
| Medium: 0.3 m/s | • 100 mm cast-iron | • Studies simulating typical water distribution systems | • Common distribution system velocity |
| High: > 0.3 m/s | • 12.5 mm copper tubing | • Studies simulating household plumbing | • Smaller diameter household tubing results in higher velocities |
| **Stagnation time** | | | |
| Intermittent (on/off) | • Flow-through configuration | • Studies simulating on/off flow conditions in household plumbing<br>• Metal release studies | • Requires valves with timers or ongoing operator supervision |
| Various times | • Flow-through configuration | • Observe the effects of various retention times on metal release | • Easy method for simulating different retention times |

However, depending on the study objectives, flow-through studies can be limited by retention time. For studies observing corrosion through chemical measures, the retention time should be long enough to observe changes in water quality. An easy way to increase retention times in a flow-through system is to incorporate stagnation times. Flow-through systems work well with long-term weight loss measures that are used to determine corrosion rates, as well as with electrochemical measures. Studies simulating residential plumbing systems are usually set up as flow-through. Retention time is not so much of an issue, since long coils of copper tubing are usually used and this type of study usually incorporates a flowing/stagnant pattern.

Recirculating flow configuration is ideal for studying equilibrium conditions, metal release and corrosion control. The recirculating flow configuration is another option to increase retention time, without increasing the overall pipe length or decreasing the velocity. Stagnation should not be used with the recirculating flow configuration.

### Retention time

Retention time is a very important design component for many studies that are observing metal release or impacts of water age on water quality. Typically, retention times are (Table 4) very short, medium or long (>36 h). It was impossible to put specific time constraints on the very short and medium retention times. In general, a very short retention time results in no difference between influent and effluent water quality, since there is not enough time for the reactions to be measurable. A medium retention time would be one that is typical of larger mains in an actual water distribution system (site dependent) and would provide observable differences between influent and effluent water quality. A long retention is one where the water quality might deteriorate to the point that the results are representative of the extremities, or low flow areas, of a distribution system. This flow regime would represent household connections, which are typically represented by stagnation periods (AWWARF, 1990). Lohmann et al. (1997) represent the extremities at pilot-scale with a retention time of 36 h, whereas Haudidier et al. (1989) had a system retention time of 10 days.

Although many distribution systems have retention times much greater than 36 h, that particular retention time may be considered long if the pipe diameter of the test loop is small relative to the full-scale system. Several studies have noted the significance of available surface area, which is inversely related to pipe diameter, for evaluating kinetics of suspended bacteria (Prévost et al., 1998) and free chlorine residual (Lu et al., 1999).

### Test section velocity

The options for test section velocity, shown in Table 4, are: no velocity, low, medium and high velocity. No velocity is used when the study has incorporated stagnation times. Low velocities may be desirable to increase retention time in a flow-through pipe rig or to observe the impact of low flow conditions on water quality. A medium velocity of 0.3 m/s (Reiber, 1993; McAnally & Kumaraswamy, 1994; MacKoul et al., 1995; Camper, 1996) is a typical water distribution system velocity and is commonly used in any study that is simulating water distribution systems. High velocities are common in test sections that have small diameters, which are typically used for simulating residential plumbing systems.

The interrelationship between entrance effects, physical changes in the pipe rig, joints in the rig and other physical factors (e.g. on-line probes) on velocity profiles within a pipe rig may be critical for medium and high velocity systems. However, there is relatively little, if any, research that quantifies the effect of velocity profiles on water quality in a pipe rig. Accordingly, the significance of velocity profiles has not been included in the framework because of a general lack of information that has been published in the literature.

Depending on the flow configuration, the retention time may or may not be a function of velocity. With a recirculating flow configuration, the velocity and flow rate are independent, as long as the velocity is high enough to model the system as a CMR. However, with a flow-through configuration, the retention time is a function of velocity. For example, a 2-m section of pipe with a velocity of 0.3 m/s would have a retention time of only 6.7 sec. Consequently the contact time for this section would probably be too short to observe any changes in water

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**Table 5** | Quality assessment techniques

| Design option | Typical corequisite | Applications/study objectives | Design considerations |
|---|---|---|---|
| Electrochemical | • No stagnation time | • Corrosion rate studies | • May require power source<br>• Provides instant measure of corrosion rate<br>• Primarily relevant for fresh metal surfaces |
| Weight loss | • Pipe inserts/coupons | • Corrosion rate studies | • May require long-term exposure<br>• Can only calculate corrosion rate at the end of the study |
| Chemical | • Long retention times | • Metal release studies | • Ensure there is a long enough retention time<br>• Cannot provide actual corrosion rate |

quality. Therefore if metal release studies or other bulk water measurements (e.g. turbidity) were important to the study objectives it would be critical to adjust the velocities to ensure an adequate contact time between the water and the pipe surface is achieved.

### Stagnation time

Stagnation occurs when the water in the pipe rig is not flowing. The conditions are ideal for metal release studies. Stagnation times can vary and there is no specific standard for choosing stagnation times. Table 4 indicates that stagnation can either be set up to operate in an on/off fashion with set flowing/stagnation durations, or to use various stagnation times to simulate the effect of varying retention times. For the latter, an experiment may look at metal release after 1, 2, 4, 8 and 12 h.

Studies that are concerned with simulating residential plumbing systems should incorporate a pattern of on/off flow that would simulate water use in the house. A typical pattern to follow would be flow occurring in the morning and evening and stagnation during the day and overnight. Although stagnation is a way to increase retention time, it should be cautioned that a 12-h retention time achieved through stagnation might affect water quality differently than a 12-h retention time under flowing conditions. Maddison *et al.* (2001) observed a sedimentation effect from calcium carbonate when dealing with long stagnation times that would not occur if the water were flowing. Furthermore, the stagnation pattern creates very specific metal release patterns, which will be induced through the presence of disinfectants and then through subsequent depletion (Lytle & Schock, 2000). Therefore it is critical that comparisons be drawn among pipe loops having similar stagnation patterns, otherwise erroneous decisions could be made as a result of incomplete information.

## Water quality assessment

### Water quality measurements

Many water quality parameters can be assessed from pipe rig studies and they are intrinsically related to the project objectives. For corrosion studies, corrosion can be measured three different ways (Table 5): electrochemically, through weight loss measures and chemically. Because drinking water is a poor electrolyte, linear polarization is widely accepted as a reliable method of electrochemical corrosion rate measurement (MacQuarrie *et al.*, 1997). Weight loss measures are normally limited when using pipe inserts or coupons. Analysis of dissolved metals is another very common method for quantifying the effect of treatment strategies on corrosion.

In addition to corrosion measurements, biofilm (e.g. Camper, 1996) is often quantified through microbial counts, microbiological speciation and through biomass estimation. Biofilm analysis normally requires that a coupon or test section can be removed during the experiment (e.g. Haudidier *et al.*, 1989). Biofilm or suspended

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cell counts are often targeted for coliform bacteria, heterotrophic bacteria and autotrophic bacteria (e.g. nitrifying bacteria). It would be plausible to quantify other species (e.g. protozoan cysts), although bacterial populations are generally more common in pipe rig studies because they are known to reproduce in full-scale distribution systems.

Furthermore, chemical indices related to disinfection such as disinfectant residuals and disinfection by-products are very important to many pipe rig investigations. As disinfectant residuals degrade during distribution, DBPs may form (e.g. trihalomethanes) or degrade during distribution (e.g. haloacetic acids). Quantifying the factors affecting the fate of these parameters in distribution could be important for establishing future regulations related to disinfection of distribution systems.

Finally, quantifying general water quality parameters, such as pH, total organic carbon, biodegradable organic matter (e.g. assimilable organic carbon), temperature, dissolved oxygen, alkalinity, total dissolved solids, disinfectant residual, sulphate and hardness would be important for most pipe rig studies, as they strongly affect the overall microbiological and chemical quality of a distribution system.

### Study duration

The study duration should be long enough to maintain stable metal levels and to be able to obtain the number of samples needed to achieve a desired accuracy and confidence in the data result. Kirmeyer *et al.* (1994) found that a pipe rig study can be divided into three distinct periods: (1) a conditioning period, (2) a transition period and (3) a stability period. Based on the pipe rigs reviewed, 3 months was the shortest duration, however most studies were 6 to 24 months, which would account for these three experimental periods identified by Kirmeyer *et al.* (1994). Therefore six months is recommended as the minimum study duration.

### CONCLUSIONS

The use of model distribution systems provides a viable means to simulate water distribution systems without affecting the integrity of the full-scale system. Common model distribution systems include pipe rigs, annular reactors and bench-scale batch reactor style tests. Pipe rigs can be more complex and designed to capture water quality conditions under more robust hydraulic conditions. Although many pipe rig studies have been conducted in the past for a variety of study objectives, there are very few standard pipe rig designs. This paper developed a design framework for designing pipe rigs based on three design categories; namely physical configuration, hydraulic conditions and monitoring criteria. The design variables and the criteria associated for each are based on pipe rigs from past studies that have been used for corrosion, corrosion control, biofilm and water quality studies. It is recommended that the design categories be viewed in a hierarchal manner, such that the study objectives influence the selection of the design categories and that the physical characteristics, in general, influence the hydraulic conditions and quality assessment used by the pipe rig.

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