DUCTILE IRON PIPE VERSUS PVC

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All Pipe Materials Are Not Equal

Design engineers must consider many factors when designing and specifying potable water pipelines, including initial cost of the system, operating requirements, maintenance costs, dependability, and long-term performance. In an effort to make that job easier, this brochure will compare the structural and performance attributes of Ductile Iron pipe and polyvinyl chloride (pvc) pipe and provide valid current information to engineers who must determine a basis for selecting piping materials.

In addition to providing physical test data comparing the two pipe products, the brochure will also compare applicable AWWA design standards for each pipe, including ANSI/AWWA C150/A21.50[1] for Ductile Iron pipe, the 1997 edition and the 2007 edition of ANSI/AWWA C900[2,3] for smaller-diameter pvc, and ANSI/AWWA C905[4] for large-diameter pvc pipe.

This brochure will also question why two different standards exist for the same pvc pipe material and why the 2007 edition of C900 greatly reduced its safety factors. Whereas Ductile Iron pipe standards have always been conservatively consistent for all sizes, the C905 and C900-07 standards for pvc pipe differ substantially from the C900-97 standard. C905 and C900-07, for example, provide for a thinner wall, greatly reduced safety factors, and no surge allowance.

Lastly, this brochure will compare the installation techniques and practical aspects of utilizing the two flexibly designed conduits. The following data are drawn from several sources, including AWWA standards, published information from pipe manufacturers and associations, and physical testing performed by research engineers from the Ductile Iron Pipe Research Association and the Robert W. Hunt Company.[5]

In short, this brochure will present sound engineering information that will prove that all pipe materials, indeed, are not equal.

Why Did the 2007 Revision of C900 Reduce its Safety Factors to that of C905?

Specifying engineers are asking, with good reason, why the 2007 revision of C900 for small-diameter pvc pipe standard incorporated several major changes in design and testing requirements.

The 2007 revision of AWWA C900 standard (3- through-12 inch pvc) and AWWA C905 Standard (14- through 48-inch pvc), for example, includes a safety factor of 2.0 for internal pressure design that is 20 percent less than the 2.5 safety factor for small-diameter pvc required by the 1997 edition of AWWA C900 (3- through 12-inch).

The 2007 edition of C900 inaccurately refers to the pipe as "pressure classes" rather than the correct "pressure rating" designation since surge pressure is not included. C905 refers to the pipe as "pressure rating."

According to a spokesman for the pvc pipe industry, "The weakness of pvc pipe is its limited resistance to surging pressure."[6] And, whereas C900-97 pvc had an allowance for surge pressure, the C900-07 and C905 standards for pvc pipe have no allowance for surge pressure in the pressure ratings.

The total internal design pressure in the C900-07 and C905 standards are less than the total internal design pressure in the C900-97 standard. For C900-97, the Hydrostatic Design Basis (HDB)/2.5 = working pressure + surge. For C900-07 and C905, the (HDB)/2.0 = working pressure. Thus, there is no surge allowance, and safety factors are greatly reduced.

Pvc C900-97 vs. C900-07 and C905 Pipe Wall Thickness Comparison

One way of realizing the inferior design of C900-07 and C905 compared to C900-97 is by comparing wall thickness. The equation for hoop stress for calculating the net thickness required for internal pressure is:

$$t = \frac{PD}{2S}$$

in which:
t = net thickness (in)
P = design internal pressure (psi)
D = pipe diameter (in)
S = design stress (psi)

Table 1 - Comparison of Ductile Iron Pipe and pvc Pipe Standards

Topic	Ductile Iron Pipe ANSI/AWWA C150/A21.50 ANSI/AWWA C151/A21.51[7]	pvc Pipe ANSI/AWWA C900-97	pvc Pipe ANSI/AWWA C900-07	pvc Pipe ANSI/AWWA C905
Sizes	3" - 64"	4" - 12"	4" - 12"	14" - 48"
Laying Lengths	18', 20'	20' ± 1"	20' ± 1"	20' ± 1"
Pressure Class/Ratings	Rated up to 350 psi. Pressure Class 150, 200, 250, 300, & 350. Higher pressures may be designed.	Rated at 100, 150 & 200 psi (DRs 25, 18, & 14, respectively) at a service temperature of 73.4°F. For service temperatures greater than 73.4°F, the pressure ratings must be appropriately reduced.	Rated at 165, 235 & 305 psi (DRs 25, 18, & 14, respectively) at a service temperature of 73.4°F. For service temperatures greater than 73.4°F, the pressure ratings must be appropriately reduced.	Rated at 80, 100, 125, 160, 165, 200, 235, & 300 psi (DRs 51, 41, 32.5, 26, 25, 21, 18, & 14, respectively) at a service temperature of 73.4°F. For service temperatures greater than 73.4°F, the pressure ratings must be appropriately reduced.
Method of Design	Designed as a flexible conduit. Separate design for internal pressure (hoop stress equation) and external load (bending stress and deflection). Casting tolerance and service allowance added to net thickness.	Designed as a flexible conduit. Separate design for internal pressure (hoop stress equation) and external load (deflection) — **external load is not covered by a standard**. No consideration for bending stress.	Same as C900-97	Same as C900-97
Internal Pressure Design	Pressure Class: Stress due to working pressure plus surge pressure cannot exceed the minimum yield strength of 42,000 psi ÷ 2.0 safety factor.	Pressure Class: Stress due to working pressure plus surge pressure cannot exceed the HDB (4,000 psi) ÷ 2.5 safety factor (HDS = 1,600 psi).	Pressure Rating: Stress due to working pressure cannot exceed the HDB (4,000 psi) ÷ 2 safety factor (HDS = 2,000 psi).	Same as C900-97
Surge Allowance	Nominal surge allowance is 100 psi (based on an instantaneous velocity change of approximately 2 fps); however, actual anticipated surge pressures should be used.	30, 35, or 40 psi surge allowance for DRs 25, 18, & 14, respectively. Based on an instantaneous velocity change of approximately 2 fps.	None included. Pressure ratings must be reduced to allow for pressure surges. Pressure surges based on an instantaneous velocity change of 2 fps would be 30, 35, & 40 psi (for DRs 25, 18, & 14, respectively).	None included. Pressure ratings must be reduced to allow for pressure surges. Pressure surges based on an instantaneous velocity change of 2 fps would be 21, 23, 26, 29, 30, 32, 35, & 40 psi (for DRs 51, 41, 32.5, 26, 25, 21, 18, & 14, respectively).
External Load Design	Prism load + truck load. Ring bending stress limited to 48,000 psi, which is 1/2 the minimum ultimate bending strength. Deflection is limited to 3% of the outside diameter of the pipe, which is 1/2 of the deflection that might damage the cement-mortar lining.	No thickness design standard for pvc pipe. The installation standard, ANSI/AWWA C605[8], places a limit of 5% on vertical cross-section deflection. Reference is made to AWWA M23[9] for design procedures. Prism load + truck load. Utilizes the Modified Iowa Deflection Equation; however, no safety factors are defined.	Same as C900-97	Same as C900-97
Live Load	AASHTO H-20, assuming a single 16,000- lb concentrated wheel load. Impact factor is 1.5 for all depths.	**Design not covered in the standard.** Reference is made to AWWA M23 for design procedures. AASHTO H-20, 16,000-lb wheel load. Impact factor of 1.1 for depths of cover between 2 and 3 feet. Impact factor of 1.0 for depths of cover of 3 feet or greater.	Same as C900-97	Same as C900-97
Factor of Safety	**Pressure Design:** 2.0 (including surge) based on minimum tensile yield strength of 42,000 psi. **External Load Design:** 2.0 for bending based on minimum ultimate ring bending strength of 96,000 psi, or 1.5 for bending based on minimum ring yield-bending strength of 72,000 psi. 2.0 for deflection for cement-mortar-lined pipe. **Note: Actual safety factors are greater than the nominal safety factors due to the addition of the service allowance and the allowance for casting tolerance in the design procedure.**	**Pressure Design:** 2.5 (including surge) based on HDB. **External Load Design:** No safety factors can be calculated. No external load criteria are defined. **Note: Safety factors and strength greatly affected by temperatures, surface scratches, and extended exposure to sunlight. Pipes under cyclic loading likely to have lower safety factors than those under static loading.**	**Pressure Design:** 2.0 (no surge included) based on HDB. In case of surge, the 2.0 safety factor is reduced. For occasional (emergency) surge the safety factor is allowed to be reduced to 1.25. For recurring surge the design is based on mean stress, stress amplitude, number of cycles to failure, and design life of the pipe. **External Load Design:** No safety factors can be calculated. No external load criteria are defined. **Note: Safety factors and strength greatly affected by temperatures, surface scratches, and extended exposure to sunlight. Pipes under cyclic loading likely to have lower safety factors than those under static loading.**	**Pressure Design:** 2.0 (no surge included) based on HDB. Section 4.6.2 cautions that when C905 pipe sizes are used in distribution systems that the safety factor may need to be set at 2.5 and an allowance for surge pressures may need to be added. **External Load Design:** Same as C900. **Note: Same as C900.**
Specified Trench Conditions	Five specified laying conditions (Types 1-5). Conservative E′ and soil strength parameters listed. Type 1 (flat bottom, loose backfill) or Type 2 (flat bottom trench, backfill lightly consolidated to centerline of pipe) are adequate for most applications.	Not covered in the standard. The Foreword of the standard references AWWA M23 and ANSI/AWWA C605. C605 contains five trench conditions referred to as "common embedment types." These trench types resemble the trench types used in the Ductile Iron pipe design standard (AWWA C150); however, AWWA C605 uses much less conservative trench values for the bedding constant (K) and soil modulus (E′) for the commonly used pvc trench types.	Same as C900-97	Same as C900-97
Hydrostatic Testing	Each pipe tested to a minimum of 500 psi for at least 10 seconds at full pressure.	Each pipe tested at 4 X designated pressure class for at least 5 seconds at full pressure. There is a provision (Section 5.1.14) for the "purchaser and/or supplier" to allow the manufacturer to conduct hydrostatic proof tests for pipes at test frequencies "other than the requirements stated." In other words, not every piece of pvc pipe "must" be pressure tested.	Each pipe tested at 2 X designated pressure class for at least 5 seconds at full pressure. There is a provision (Section 5.1.14) for the "purchaser and/or supplier" to allow the manufacturer to conduct hydrostatic proof tests for pipes at test frequencies "other than the requirements stated." In other words, not every piece of pvc pipe "must" be pressure tested.	Same as C900-97 except section 5.1.14 is section 5.1.9
Factory Tests	At least one sample during each casting period of approximately 3 hours shall be subjected to a tensile test; must show minimum yield of 42,000 psi, minimum ultimate of 60,000 psi and minimum elongation of 10%. At least one Charpy impact sample shall be taken per hour (minimum 7 ft-lb), with an additional low-temperature impact test (minimum 3 ft-lb) made from at least 10% of the sample coupons taken for the normal Charpy impact test.	Sustained pressure test (1,000 hours) is run semi-annually at approximately 3.25-3.5 times the pressure class. Quick burst strength (at approximately 5 times the pressure class) tested once every 24 hours. Flattening resistance tested once every 8 hours as specified in ASTM D2412[10]. Extrusion quality tested once every 8 hours as specified in ASTM D2152[11].	Sustained pressure test (1,000 hours) is run semi-annually at approximately 2.12 - 2.13 times the pressure class. Quick burst strength (at approximately 3.23 times the pressure class) tested once every 24 hours. Flattening resistance tested once every 8 hours as specified in ASTM D2412[10]. Extrusion quality tested once every 8 hours as specified in ASTM D2152[11].	Flattening resistance tested once every 8 hours as specified in ASTM D2412. Extrusion quality tested once every 8 hours as specified in ASTM D2152. Quick burst and sustained pressure tests are not required.

Therefore, the net pipe wall thickness increases as the diameter increases for constant design internal pressure. However, 100 psi pressure class 12-inch diameter pvc (C900-97) has a wall thickness of 0.528-inch where 100 psi pressure rated 14-inch-diameter pvc (C905) has a wall thickness of only 0.373-inch (less than the smaller 12-inch diameter pipe). This is contrary to all basic engineering reasoning.

100 psi Pressure Class/Pressure Rating
C900-97 Standard 12-inch-diameter pvc
t = 0.528"
C905 Standard 14-inch-diameter pvc
t = 0.373"

Another way of comparing the design of C900-97 and C900-07 is to calculate the pipe wall thickness for the same diameter pipe using both designs. For 200 psi pressure class, a 12-inch-diameter pvc pipe would require a wall thickness of 0.943 inches based on C900-97. However, based on C900-07, the same pipe would require a wall thickness of only 0.629 inches (33 percent less than C900-97).

200 psi Pressure Class/Pressure Rating
C900-97 Standard 12-inch-diameter pvc
t = 0.943"
C900-07 Standard 12-inch-diameter pvc
t = 0.629"
(a 33-percent reduction in wall thickness)

Pvc C900-97, C900-07 and C905 Physical Testing Requirements Comparison

Not only design requirements but also physical testing requirements have been reduced in the C900-07 standard. The hydrostatic test pressure in C900-07 has been reduced. In C900-97, hydrostatic test pressures are four times the designated pressure class. In C900-07, on the other hand, they are only two times the designated pressure rating. Also, C905 does not require the quick burst or sustained pressure tests required by C900-97 and C900-07.

The 1997 revisions of C900 and C905 incorporated a new section titled "Additional Test Requirements" which was changed to "Optional Test Frequency" in the 2007 revision of C900. This title is misleading because the new section does not require additional testing. Rather, it gives the purchaser or supplier the option to allow the manufacturer to conduct hydrostatic proof tests of pipe (and also couplings in C900) at frequencies less than specified in pertinent sections of the standards. These sections, pertaining to the proof tests, require that "each standard and random length of pipe" and each coupling be subjected to hydrostatic proof tests. Therefore, the purchaser or supplier (which could be a distributor or contractor) could specify, for example, that only every 10th, or every 100th, piece of pipe be tested. To preclude such an occurrence, specifications should require certification by the manufacturer that each piece of pipe and each coupling have been subjected to proof tests in accordance with the standard.

These are just a few of the reduced requirements in the C900-07 and C905 standards for pvc, which could result in an inferior product compared to C900-97-designed pipe. Table 1 highlights examples of shortcomings in the C900-07 and C905 standards compared to C900-97 and compares them to requirements of ANSI/AWWA C150/A21.50 and ANSI/AWWA C151/A21.51.

Ductile Iron Pipe Has More Than Eight Times the Tensile Strength of pvc

The pipe material's tensile strength is a very important basic property because it resists the forces caused by internal hydrostatic pressure and water hammer.

Figure 1 compares the tensile strengths of Ductile Iron and pvc pipe. Shown for comparison are minimum values per the applicable standards as well as test data from actual measurements of specimens taken from the wall of 6-inch Pressure Class 350* Ductile Iron pipe and 6-inch DR 18 (PR 235, previously PC 150) pvc pipe.

* Pressure Class 350 is the lowest available pressure class for 6-inch Ductile Iron pipe.

Typical Variations in Operating or Installation Temperature Do Not Affect the Strength of Ductile Iron Pipe

Because Ductile Iron pipe has a moderate and dependable coefficient of thermal expansion, few problems are created by changes in service temperatures. Also, in a typical range of waterworks operating temperatures (32°F to 95°F) or even a conceivable range of installation temperatures (-10°F to 110°F), there is no significant difference in the tensile strength of Ductile Iron pipe.

On the other hand, because of its high thermal expansion coefficient, the performance of pvc pipe is significantly related to its operating temperature.[12] For service at temperatures greater than 73.4°F, pvc loses tensile strength, pipe stiffness, and dimensional stability. Thus, the pressure capacity of the pvc pipe is reduced, and more care must be taken during installation to avoid excessive deflection.[13]

Conversely, at temperatures less than 73.4°F, pvc loses impact strength and becomes less ductile, necessitating greater handling care in colder weather.[14] Because the thermal expansion coefficient of pvc is approximately five times that of Ductile Iron pipe,[15] it is conceivable that, when exposed to extreme temperature changes, pvc pipe will experience undesirable structural movements such as joint buckling or disengagement because of expansion or contraction.

Figure 2 shows the relationship based on the standard tensile strength of 7,000 psi for pvc. At 110°F, the tensile strength of pvc is approximately half of the tensile strength at 73.4°F.

Figure 1 - Tensile Strength

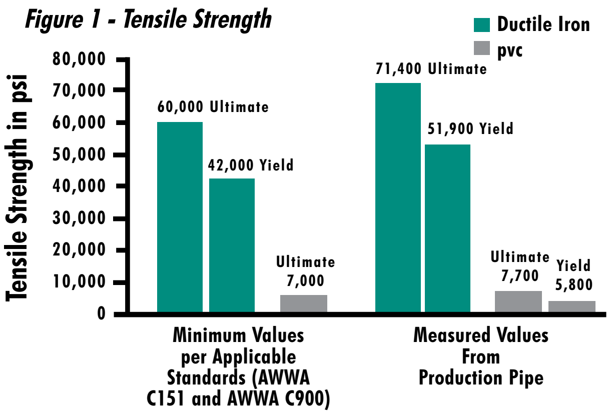
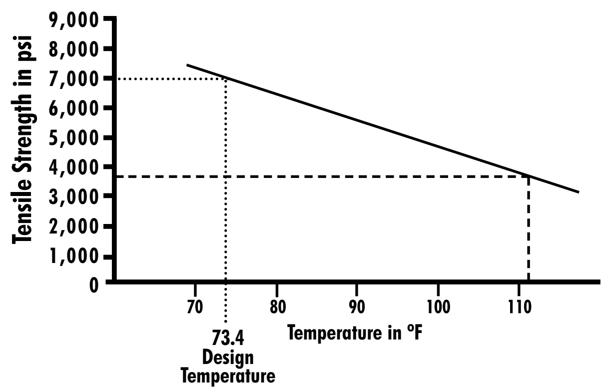


Figure 2 - Strength-Temperature Relationship for pvc



Ductile Iron Resists Up to Four Times the Hydrostatic Burst Pressure of pvc Pipe.

The burst test is the most direct measurement of a pipe material's resistance to hydrostatic pressure.

Figure 3 compares the average burst pressure of 6-inch Pressure Class 350* Ductile Iron pipe and 6-inch DR 18 (PR 235, previously PC 150) pvc pipe. Note that Ductile Iron pipe is available in pressure ratings up to 350 psi in all sizes, 3-inch to 64-inch. No pvc pipe — C900 or C905 — is manufactured with a pressure rating as great as that of Ductile Iron pipe.

* Pressure Class 350 is the lowest available pressure class for 6-inch Ductile Iron pipe.

Figure 4 compares the hydrostatic burst pressure of 24-inch Pressure Class 200* Ductile Iron pipe and 24-inch DR 25 (PR 165) pvc pipe. In laboratory tests, the average burst pressure of the 24-inch Ductile Iron pipe was 1,523 psi. For the pvc pipe, it was 527 psi — approximately one-third that of Ductile Iron pipe.

Figure 3 - Hydrostatic Burst Pressure—6-inch Ductile Iron and pvc Pipe

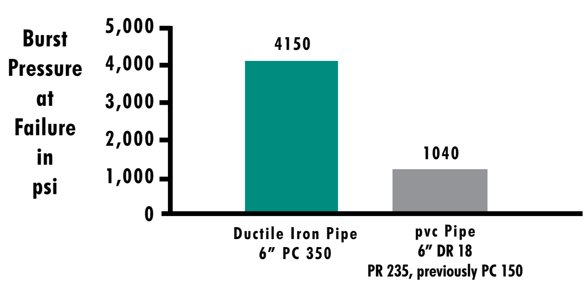
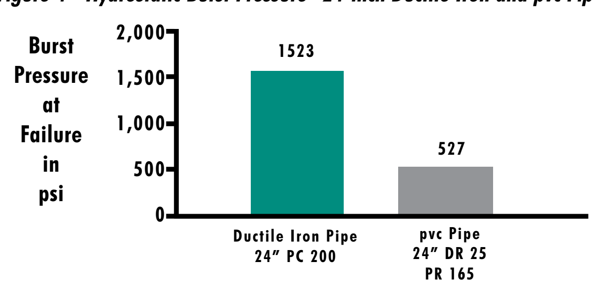


Figure 4 - Hydrostatic Burst Pressure—24-inch Ductile Iron and pvc Pipe



* Pressure Class 200 is the lowest available pressure class for 24-inch Ductile Iron pipe.

The Strength of Ductile Iron Pipe Is Not Compromised By Time.

With Ductile Iron pipe, there is no measurable relationship between applied tensile strength and time to failure. Thus, the strength for hydrostatic design of Ductile Iron pipe is its minimum yield strength in tension, 42,000 psi.

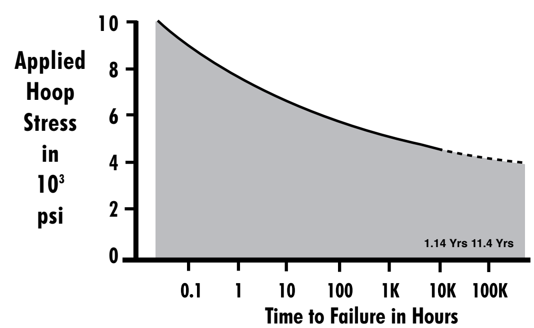
Pvc responds to tensile stress by failing after a period of time inversely related to the applied stress. Thus, the strength used for hydrostatic design of pvc pipe is less than the yield strength of the material as established in a short time test.[16] The strength value used is called the long-term hydrostatic strength and is also referred to as the Hydrostatic Design Basis (HDB).

The HDB value, which is defined as the stress that results in failure after 100,000 hours (11.4 years), is determined according to ASTM standard procedures by extrapolation from data accumulated from tests lasting up to 10,000 hours (1.14 years).[17] For the pvc compound used in C900 and C905 pipe, the HDB is 4,000 psi.[18] The HDB will be less than 4,000 psi for pvc pipe used at temperatures greater than 73.4°F.[19]

Since no utility wants its pipe to last only 11.4 years, a nominal factor of safety is applied to the long-term hydrostatic strength. The nominal factor of safety depends upon the standard under which the pipe was manufactured. For ANSI/AWWA C905 and ANSI/AWWA C900-07, the factor of safety is 2.0. For ANSI/AWWA C900-97, the factor of safety was 2.5, which also included a surge allowance based on two-feet-per-second instantaneous velocity change. Both of these designs are based strictly upon hydrostatic pressure and do not take into account any other localized stresses that may occur during installation or in operation over time, nor do they account for possible fluctuations in pressure. Yet these factors may have a great effect on the life expectancy of the pipe.

Figure 5 is a typical stress regression curve for pvc pressure pipe. The stress regression curve is a plot of failure points that demonstrates pvc's ability to withstand stress as a function of the magnitude of the stress and the length of time that stress is applied. Thus, the stress regression curve is a representation of the length of time until failure of the pvc at a given level of stress. And, as the curve shows, the higher the stress the shorter the expected life for pvc pipe.[20]

Figure 5 - Typical Stress Regression Curve for pvc Pressure Pipe[21]



Ductile Iron Pipe Resists Up to Eight Times the Crushing Load of pvc Pipe.

The different theories of design of buried pipelines become most significant in relation to external load design. Both Ductile Iron and pvc pipe, being flexible rings, respond to external load by deflecting.[22] The interaction of the deflected ring with the surrounding soil is the complex question in the design theories.

The design procedure for Ductile Iron pipe is based on limiting both the ring bending stress and deflection, while the only parameter used in the design of pvc pipe is ring deflection.

The standard design procedure for Ductile Iron pipe limits the ring deflection due to external loads to 3 percent. This limit, which is based on the performance limit for cement-mortar linings typically specified for Ductile Iron pipe, includes an explicit safety factor of 2. This calculation employs the same conservative assumptions regarding soil parameters and earth loads used in the bending stress calculation.

The usual design procedure for pvc limits ring deflection to 5 percent[23] — the only consideration given to external loading.

Both Ductile Iron and pvc pipe design procedures employ the Iowa formula to predict deflection of the pipe.[24] In the Iowa formulation, both pipe stiffness and the stiffness of the fill material around the pipe contribute to limiting the deflection. Because pvc pipe has far less stiffness than Ductile Iron, the importance of soil stiffness is greater for pvc. This means that with pvc pipe, bedding conditions and on-the-job installation inspection are much more critical.

The parallel plate ring crush test provides a simple comparison of the relative strengths of the two piping materials. Figure 6 compares pipe stiffness resulting from such tests conducted on 6-inch Pressure Class 350* Ductile Iron pipe and 6-inch DR 18 pvc pipe (C900). Likewise, Figure 7 compares pipe stiffness of 24-inch Pressure Class 200** Ductile Iron pipe and DR 25 pvc pipe (C905).

* Pressure Class 350 is the lowest available pressure class for 6-inch Ductile Iron pipe.
** Pressure Class 200 is the lowest available pressure class for 24-inch Ductile Iron pipe.

Figure 6 - Pipe Stiffness Comparison of 6-inch DIP and pvc

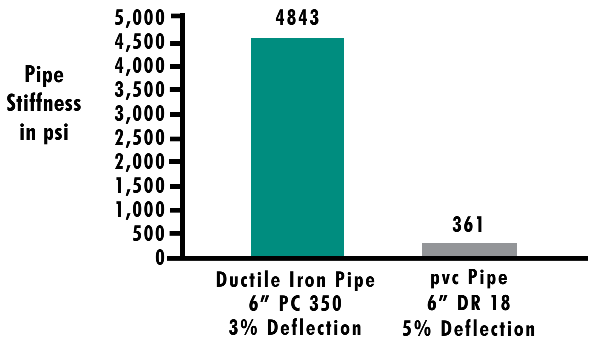
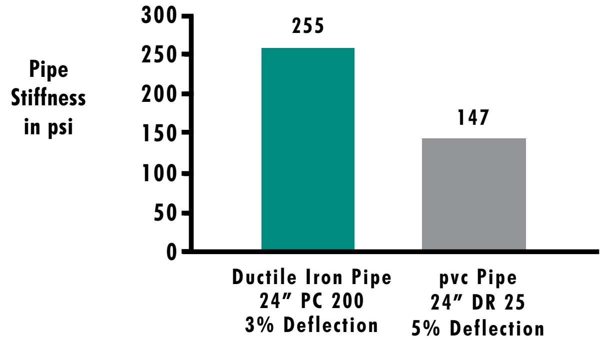


Figure 7 - Pipe Stiffness Comparison of 24-inch DIP and pvc

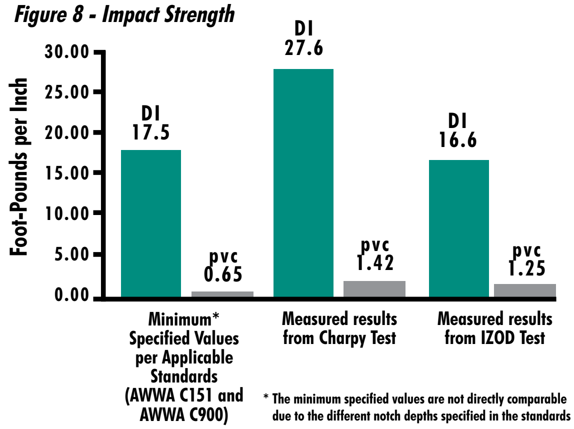


Ductile Iron Has More than 13 Times the Impact Strength of pvc.

Impact strength is another important characteristic of piping materials. While this property relates more to conditions the pipe might encounter during handling, shipping, and installation, it is nevertheless important because damage incurred during these activities can go undetected and later result in failures in the operating pipeline.

Figure 8 compares the impact strength as specified and measured for Ductile Iron and pvc, which were tested by both the IZOD (cantilevered beam) and Charpy (simple beam) methods.[25] These values are representative of tests conducted at 73.4°F. As with tensile strength, there is no measurable relationship between impact-resistance and temperature within expected ranges for Ductile Iron pipe. Pvc pipe, however, exhibits a measurable decrease in impact strength at temperatures below 73.4°F.[26] The impact strength of pvc is also measurably decreased after the pipe has been overexposed to sunlight — an important consideration in storing pvc pipe stocks.[27]

Figure 8 - Impact Strength



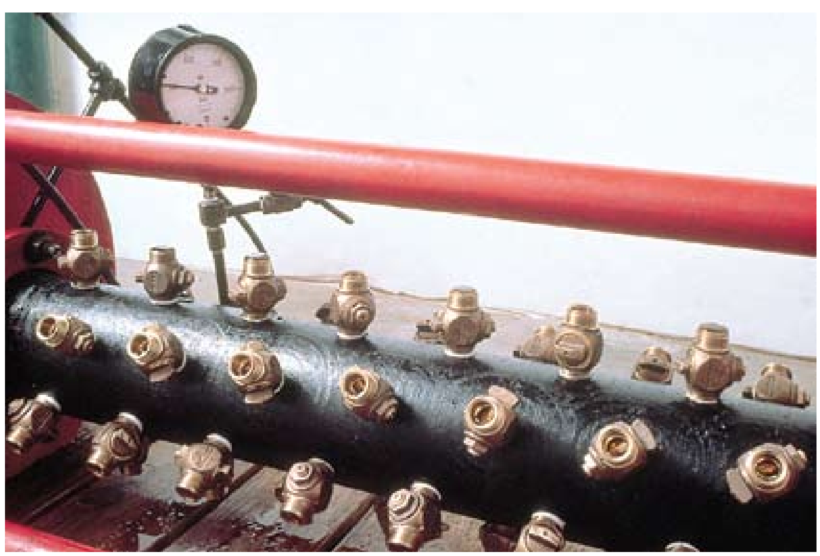
* The minimum specified values are not directly comparable due to the different notch depths specified in the standards

Direct Tapping Ductile Iron is Easier, Less Expensive, Faster — and Less Likely to Damage the Pipe — Than Tapping pvc.

DIPRA conducted tests comparing several different parameters concerned with the direct tapping of 5-foot lengths of 6-inch Pressure Class 350 Ductile Iron pipe and 6-inch DR 14 (PR 305, previously PC 200) pvc pipe, including leak tests, pull-out tests, and cantilever load tests.[28] Each material was tapped according to manufacturers' directions by the same machine operator. The results follow.

Leak Tests

For each material, after the tap was made at 50 psi internal pressure, pressure was increased in 25-psi increments to each pipe's maximum pressure rating at the time (350 psi for Pressure Class 350 Ductile Iron and 200 psi for DR 14 pvc). The 2007 revision of C900 reduced the safety factor from 2.5 to 2.0, resulting in the same DR 14 Pressure Class 200 pipe now being rated at 305 psi. The higher internal pressures now allowed for DR 14 pipe will likely result in more leakage for pvc pipe than was reported for these test.



Eight 3/4-inch taps were made on five pvc specimens. The corporation stops were torqued to 27 ft-lbs according to manufacturers' directions. Of the eight direct taps, five leaked prior to reaching the final 200 psi internal pressure. **All leakage occurred at the threaded connection of the pvc pipe and corporation stop.** Each of the five leaking connections was retorqued to 35 ft-lbs and internal pressure was increased. Each of these connections continued to leak prior to the pipe's 200 psi working pressure.

According to the *Handbook of PVC Pipe - Design and Construction*, if a pvc pipe continues to leak after a corporation stop is torqued to 35 ft-lbs, the water main must be taken out of service, the corporation stop removed, threads inspected and cleansed, and the corporation stop reinstalled with 27 ft-lbs of torque and rechecked.[29]

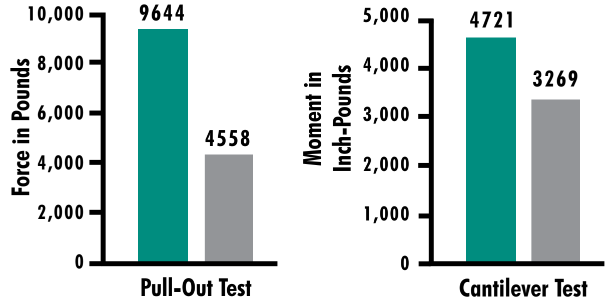
Six 3/4-inch direct taps were made on Ductile Iron pipe specimens, which were initially torqued to 30 ft-lbs. Only one exhibited any leakage, which was observed at the threaded connection to the pipe at an internal pressure of 175 psi. This corporation stop was then retorqued for 40 ft-lbs to stop the leak. After retorque of this single corporation, **none of the connections exhibited any leaks, even at 500 psi, the pressure at which the tests were terminated.**

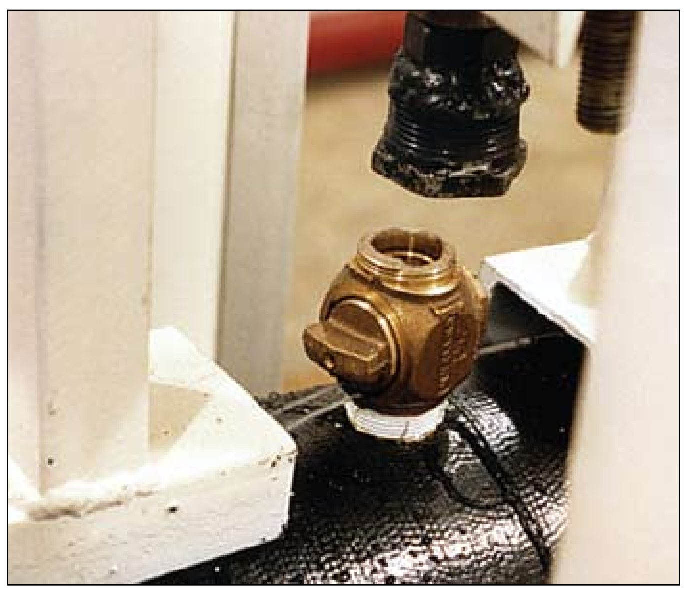
Retention of Corporation Stops

Another significant point of comparison is the vulnerability of damage to service connections. Figure 9 depicts the pull-out force and moment required to break off a 3/4-inch service tap in 6-inch Ductile Iron and pvc pipe, both in tension and as a cantilever.

The dramatic difference in values is even more significant because the failures of taps in the Ductile Iron pipe tests were failures of the brass corporation stops. No damage was inflicted on the pipe. In each case, failures of the taps in pvc pipe were failures of the pipe wall itself. This distinction is very important to the relative difficulty of repair.

Figure 9 - Corporation Stop Retention Average Load to Failure





Research shows that the strength of Ductile Iron pipe walls exceeds the strength of the corporation stop, unlike pvc pipe walls. When stressed with either cantilever or pull-out loads, taps in Ductile Iron pipe do not result in failure of the pipe walls. Photos of pull-out tests on pvc pipe show that leakage occurred at the threaded connection to the pipe, causing the pipe wall to break in the area of the corporation stop. During the same tests, leakage occurred in Ductile Iron pipe on the corporation stop plugs, as shown in the photo, and not the threaded connection to the pipe. Failure occurred at the threaded connection for the service line, not the threaded connection to the pipe.

Use of Tapping Saddles

C900 pvc pipe requires the use of a tapping saddle on certain thicknesses — and the integrity of direct tapping is questionable for all pvc thicknesses. Tapping saddles are required on all thicknesses of C905 pvc pipe.[30] On the other hand, the use of tapping saddles with Ductile Iron pipe for normal house services is unnecessary.

Tapping Advantages for Ductile Iron Pipe

When performing service taps on pvc pipe it is important to follow the guidelines laid out both in ANSI/AWWA C605 and the manufacturers' installation guides.

A review of the tapping procedures outlined in the Johns-Manville (J-M) Blue Brute installation guide[31] reveals many "Do nots." For example:
- "Do not tap into an area of the pipe which shows discoloration (sun burning)."
- "Do not tap on the outside of the curve on a pipe that has been bent (deflected) beyond the recommended radius of curvature."
- "Do not create ovality or otherwise distort the pipe by over tightening the tapping machine or the saddle."
- "Do not force the cutter through the pipe wall, make cuts slowly and use the follower very lightly. Do not use pipe dope or other liquid thread sealants."

J-M also expresses additional concerns: Do not "direct tap…Blue Brute if the system is going to operate over 85ºF." But, on the other hand, "Tapping in cold weather (below 40ºF) requires additional care because the pipe loses some of its resiliency and can become more brittle and subject to damage if abused during handling. Damage done prior to tapping can show up when the pipe is tapped." The J-M installation guide goes on to provide explicit safety precautions for tapping pvc pipe under pressure: "When tapping pressurized pvc water pipe, basic safety precautions are advised to prevent personal injury to the workman in the event of sudden and unexpected pipe failure. (They include:)

1. Do not enter a trench or hole to perform tapping procedures without a second workman or supervisor present in the immediate vicinity.
2. In addition to normal protective clothing, goggles or a face shield should be worn.
3. Prepare a means of simple and quick exit from the work area in the event of flooding. A sturdy ladder is recommended.
4. The exposed pipe in the area of the taps should be covered with a heavy protective blanket. This protective blanket should be approximately 4 feet x 6 feet in size and should have a hole in the center to permit installation and operation of the tapping machine."

According to these instructions, a 4-foot x 6-foot excavation is needed to accommodate the safety blanket and properly make a tap in accordance with the manufacturer's recommendations. Unlike Ductile Iron pipe, which has been safely tapped numerous times in tapping contests, there are case histories of people being injured while tapping pvc pipe. If bending the pipe adds stresses that increase the likelihood of a tapping failure, one hopes that a sufficient length of pvc pipe is exposed to discern whether the pipe to be tapped has been bent.

The J-M installation guide provides explicit safety precautions for tapping pvc pipe under pressure. One of those precautions is to "prepare a means of simple and quick exit from the work area in the event of flooding. A sturdy ladder is recommended." With pvc pipe failures such as these, such advice is worthwhile.

Flow Considerations

Flow Tests

DIPRA performed flow tests on in-service piping in Blackwood, New Jersey, Dothan, Alabama, and Wister, Oklahoma to establish representative Hazen-Williams "C" factor values and compare overall flow characteristics of 12- and 18-inch Ductile Iron and pvc pipe.[32]

In the 12-inch-diameter Blackwood tests, the inside diameter of the cement-mortar-lined Ductile Iron pipe was 5.8 percent larger than that of the pvc pipe — 12 percent more flow capacity. Although the pvc pipe had a slightly larger "C" factor value (indicating a slightly smoother internal pipe surface), head loss was less for Ductile Iron pipe than for pvc because of Ductile's larger inside diameter.

In the 12-inch-diameter Dothan tests, Ductile Iron's inside diameter was 5.4 percent larger than that of the pvc specimen — an 11.1 percent larger capacity. Pvc's smaller inside diameter resulted in a constant 11.1 percent higher velocity and a 23.5 percent higher head loss than the Ductile Iron pipe although both pipe sections carried the same quantity of water.

In the 18-inch-diameter Wister tests, the inside diameter of the cement-mortar-lined Ductile Iron pipe was 8.5 percent larger than that of the pvc pipe — 17.7 percent more flow capacity. Although the pvc pipe had a slightly larger "C" factor value (140.6 versus 138.6), the pvc's smaller inside diameter resulted in a constant 17.7 percent higher velocity to deliver the same quantity of water with a resultant 44.9 percent higher head loss than in the Ductile Iron pipe.

Energy Savings

Ductile Iron pipe's larger inside diameter results in significant energy savings, whether the savings are based on pumping costs or equivalent pipeline considerations.[33]

Because of Ductile Iron's larger-than-nominal inside diameter — and resulting lower pumping costs — utilities can save appreciably on power costs and continue to save money every year for the life of the pipeline.

By using equivalent pipeline theories, utilities can realize immediate savings with Ductile Iron pipe. Because of Ductile Iron's lower head loss, pvc pipelines with equivalent head loss would require larger — and, thus, more expensive — pipe diameters over portions of the pipeline. For example, a 30,000-foot-long 24-inch Pressure Class 200* Ductile Iron pipeline delivering 6,000 gallons per minute would have the same total head loss as 23,920 feet of 24-inch plus 6,080 feet of 30-inch Pressure Rated 165 pvc pipe.

* The minimum pressure class available for that diameter pipe.

Other Considerations

Pipe Handling

Pvc pipe manufacturers claim that pvc pipe is easier to handle than Ductile Iron pipe because it is lighter. But this ostensible advantage is greatly overrated. When pipe is delivered to a job site, it should always be checked while still on the truck for damage and to ensure that the load is securely fastened and can be unloaded in a safe manner. AWWA standards and manuals for both pvc[34] and Ductile Iron[35] pipe require proper equipment and methods for handling pipe and preclude rolling or dropping pipe into the trench. Pvc is lighter than Ductile Iron; however, an 8-inch DR 14 pvc pipe weighs 230 pounds, not an insignificant weight for a person to handle. Twelve-inch DR 18 pvc weighs approximately 400 pounds. Even two men should not attempt to handle a load of this magnitude. Each individual utility or contractor may have its own guidelines for what a safe load for one person is; however, 200 pounds exceeds the safe load for the vast majority of workers. Thus, the same equipment is needed to safely unload and lower both Ductile Iron and pvc pipe into the trench.

Handling Damage

Compared to Ductile Iron pipe, pvc is a very soft material and is consequently much more vulnerable to abrasions, scratches, and other damage during shipping and installation. In fact, both the C900 and C905 standards state that the "pipe surface shall be free from nicks and significant scratches."[36]

Improper handling of pvc pipe can lead to impact damage, scratching, or gouging of the pipe wall. If such handling results in a scratch or gouge that is more than 10 percent of the wall thickness, ANSI/AWWA C605 recommends rejection of the damaged pipe upon delivery[37]. If the damage occurs during installation, the damaged section should be cut from the rest of the pipe and removed. On an 8-inch DR 18 pvc pipe, a 10-percent scratch (0.05-inch) is approximately the thickness of a dime! It is recommended that the inspector on a pvc pipe job be equipped with the proper gauge to measure such damage as might occur when the pipe is handled and installed.

Ductile Iron pipe, on the other hand, is a tough material that is not usually scratched or gouged by the type of rough handling that can damage pvc pipe. Furthermore, the gouge resistance of pipe materials, along with tensile/compressive strengths, is becoming increasingly important with demanding new trenchless installation methods such as horizontal directional drilling (HDD) and pipe bursting. Because of Ductile Iron's great strength and durability, there is no measurable loss of strength due to scratches and gouges from normal handling.

Water Hammer and Cyclic Loadings

Both Ductile Iron and pvc pipe are subjected to cyclic stresses from water hammer caused by velocity changes in the system. Ductile Iron pipe has excellent resistance to such cyclic stresses. Robert T. Hucks has reported, however, that the hydrostatic design basis (i.e., the stress level resulting in failure in 11.4 years) of pvc is actually less under cyclic loading conditions than under static loading conditions.[38] In fact, Hucks proposed a cyclic hydrostatic design basis be used that would limit stress in the wall of pvc pipe to 1,000 psi. This reflected a factor of safety of 1.5 to 1 with respect to the fatigue limit of pvc pipe, which, Hucks noted, tests had shown to be 1,500 psi. The number of cycles until failure is also reduced by surface scratches on the pipe to a degree depending on their severity. According to Hucks, tests performed on plastic pipe have shown that a scratch 0.01 inches in depth and 10 inches in length on a 1 $^{1}/_{2}$-inch 160 psi pressure rated pipe reduced the cycles to failure from 52,000 to 9,600.[39] This critical depth is about 1/32-inch for 6-inch Class 150 pvc pipe. This property is not taken into consideration in the suggested pvc design procedures.

Bedding Requirements /Trenching Considerations

Due to the inherent weaknesses in pvc pipe, bedding conditions are much more critical than with Ductile Iron pipe. Proper bedding is required to control deflection, which is the single criterion in design of pvc pipe for external loads. Standards dealing with recommended installation practices for plastic piping suggest that the pipe be surrounded by a soil with a minimum particle size so that the soil can be sufficiently compacted to develop uniform lateral passive soil forces.[40] The soil also must be free of organic matter. The trench bottom must be smooth and free from large stones, large dirt clods, and any frozen materials, as these objects could cause a reduction in strength due to scratches or abrasions.[41]

Excavating for pressure piping should result in a smooth, flat-bottom trench. The designer in all cases assumes that an equal and uniform bedding condition is to be provided throughout the length of the pipeline. This reduces the potential for beam or point loads along the length of the pipe during installation. Bell holes are required in soils that are not soft enough to absorb the bell and still allow the uniform support along the barrel that is desired for any pipe material. If bell holes are not provided for pvc pipe, the pipe may be bent or point loadings may be applied that impart additional localized stresses to the pipe. Such stresses are the enemy of a long life expectancy for pvc pipe.

The required type of trench and pipe embedment depends on a pipe's stiffness, strength, and ability to withstand trench loads. Most designers require compacted bedding and select backfill in and around weaker flexible conduits. In some design situations, pvc requires select fill and compaction where the stronger Ductile Iron would not.

Standards for both pvc and Ductile Iron pipe include laying conditions for installation of their respective products. Interestingly, the diagrams shown in the installation standard for pvc pipe,[42] AWWA C605, greatly resemble those shown in the design standard for Ductile Iron pipe,[43] AWWA C150. Even the descriptions of these laying conditions are practically the same. However, this first glance does not reveal the true differences in those laying conditions — differences that reflect the advantage of installing a stronger pipe material.

The most important aspect of a laying condition is found in the resulting "Modulus of Soil Reaction," or E′, in the standards. An empirical value, E′ is used to classify the level of support that sidefill soils will offer the pipe in sustaining an external load. The most supportive trench for pvc pipe (Type 5 from AWWA C605) assumes an E′ value of 2,000 psi. This is contrasted with an E′ value for Ductile Iron pipe, for the same basic trench (Type 5 from AWWA C150), of just 700 psi. Thus, pvc pipe expects — and depends upon — nearly three times the support from backfill as does Ductile Iron pipe. The lower value reflects a lesser reliance by Ductile Iron pipe on its backfill to help sustain a given external load. It also reflects a more practical acknowledgement of what can routinely be accomplished in construction. An E′ of 2,000 psi cannot be accomplished throughout the pipe zone without careful installation and compaction of the granular and select backfill material. An E′ of 700 psi can be effectively achieved with much less effort and expense.

Because of Ductile Iron pipe's inherent strength, Type 1 (flat bottom, loose backfill) or Type 2 (flat bottom, lightly consolidated backfill) trench conditions in accordance with ANSI/AWWA C150/A21.50 are adequate for the vast majority of applications.

Joint Deflection

Existing underground utilities sometimes are found in unexpected locations, and other unforeseen obstructions are often encountered during construction. Field engineering then comes into play, and the pipeline must be reoriented and rerouted to avoid the obstruction.

"Depending upon pipe size and joint design, the deflection per joint for gasketed pvc pipe joints in the unstressed condition varies from about one-third to five degrees," according to AWWA M23.[44] Curves requiring greater deflection require special fittings or actual deflection of the pipe itself, which places stress in the pipe wall.[45]

With Ductile Iron pipe, however, no joint stress is required to obtain sufficient deflection. Depending on pipe diameter, push-on-joint Ductile Iron pipe has a joint deflection of up to 5° and mechanical-joint up to 8.3°.[46] Ductile Iron pipe fitted with ball and socket joints has a maximum deflection of up to 15° per joint in sizes up to and including 24-inch pipe; in sizes 30-inch and larger, maximum deflection varies from 12 1/2° to 15°.[47]

Restrained Joints

Because restrained joints are not readily adaptable to pvc pipe, only a limited number of joint-restraining means are available for use with that pipe. Moreover, because all pvc restrained-joint mechanisms rely on grooved or serrated edges that dig into the pipe, they can potentially cause surface scratches to the piping material. Over time, these gouges may exceed the

10-percent wall thickness warned against in ANSI/AWWA C605. These systems may also result in localized stress in the pvc material that can reduce the design life of the pipe. Remember that additional thicknesses for service and casting allowances are added to Ductile Iron pipe design, but not for pvc — despite the fact that the tensile strength is less for pvc than for Ductile Iron pipe. Therefore, many utilities require that thrust blocks, rather than restrained joints, be applied to any point in the pvc piping system where the direction or cross sectional area of the waterway changes.

On the other hand, a wide variety of restrained joints are readily available for Ductile Iron pipe, giving the designer greater flexibility in pipeline design and installation.

Locating Pipe

Because it is a non-metallic substance, buried pvc pipe cannot be located using metal detectors. Therefore, it can be very difficult to locate pvc pipe; however, it must be done to avoid damage. When plastic pipe is known to exist in the right of way, additional time might be required to pothole excavations in order to locate the pipe. Ductile Iron pipe, on the other hand, can be easily located using conventional pipe locators commonly used by most utilities.

It is necessary for utilities to provide field location of their existing facilities to others planning excavations in the vicinity. One-call systems have been established in order to help avoid damage to existing underground utilities. Thus, locating piping materials is an important part of the future operation and maintenance of a piping system. As noted above, locating Ductile Iron pipe is easy and convenient with virtually all locating equipment available on the market. Locating non-metallic pipe is difficult at best. Very often, tracer wires and excavation tapes are installed in an effort to reduce the difficulty of locating these pipes. When tracer wires are used, they should be tested after installation to be sure that they are electrically continuous from one access point to the next. Typically, access points would be at valve boxes, hydrants, etc. If the wires are not tested, then it is not known whether the system is working when it is initially installed. As an alternative to an electrically continuous tracer wire, a heavy gauge wire that can be detected with conventional locating equipment, even when conductivity is lost, can be used.

Nearby Excavation

Existing pvc pipe is substantially more vulnerable than is Ductile Iron pipe to puncture or damage during excavation and construction of nearby pipelines.

Buoyancy

Pvc pipe is buoyant — a concern when installing the pipe material in areas having a high water table or when trench flooding is likely to occur. To prevent loss of completed pipe embedment through flotation of the pvc pipe, it must be anchored.[48] Flotation is generally not a concern with Ductile Iron pipe.

Sun Exposure

Special precautions must be taken when pvc pipe is exposed to sunlight for an extended period of time, because “when subjected to long-term exposure to ultraviolet (UV) radiation from sunlight, pvc pipe can suffer surface damage. This effect is commonly termed ultraviolet (UV) degradation.”[49] According to AWWA C605, if plastic pipe is stored outdoors, it may require protection from weathering in accordance with manufacturers’ recommendations. And the covering should allow air circulation in and around the pipe.[50]

The J-M installation guide states that, “when pvc is exposed to the sunlight for long periods of time, a slow discoloration of the pipe may occur. This discoloration is an indication of a possible reduction in impact strength.”[51]

Although the long-term effects on pvc pipe exposed to sunlight have not been clearly determined, changes in material properties obviously occur since warnings are given concerning impact strength.

Ductile Iron pipe is not vulnerable to the effects of exposure to sunlight or weathering.

Permeation

There is also a problem where soils contaminated with hydrocarbons such as gasoline or other chemicals are encountered. Plastic pipe walls and gasket materials are susceptible to permeation that can damage the material and contaminate the water. In a study conducted by the Sanitary Engineering and Environmental Health Research Laboratory at the University of

California at Berkeley,[52] pvc was reported to be involved in 15 percent of the permeation incidents found in a literature search in the United States. Other agencies have also investigated occurrences of this phenomenon.[53] Interestingly, the University of California report also notes that, previously, pvc pipe had "been considered as relatively immune to permeation. . ."[54]

On the other hand, this study revealed only one incident where a gasket was permeated. In Ductile Iron pipe, the only opportunity for permeation is at the gasket. The standard gasket used in push-on and mechanical joints is made from the elastomer styrene butadiene (SBR). Even though the University of California report cites just one occurrence of a permeated gasket, should contaminated soils be encountered in design, gaskets made of permeation-resistant materials such as Nitrile or fluorocarbon may be specified. In other words, while pvc pipe cannot be made to be resistant to soils containing permeants, Ductile Iron pipelines can.

Another Environmental Factor

As a final observation regarding environmental considerations, it should be noted that pvc is made from petroleum derivatives, chlorine gas, and vinyl chloride, the latter two substances being of concern in environmental circles, while Ductile Iron pipe is manufactured using recycled scrap iron and steel.

Performance History

The performance of Ductile Iron pipe extends over 50 years, and because of its close physical resemblance to gray Cast Iron pipe, the long-term record of Cast Iron can be used to predict the life of a Ductile Iron pipeline.[55] This comparison has been enhanced by extensive research on the comparative corrosion rates between Ductile Iron and gray Cast Iron, which has shown Ductile Iron to be at least as corrosion-resistant as gray Cast Iron.[56]

Conclusion

This brochure has presented major considerations facing design engineers when deciding what type of piping material to specify for any given application. Evidence has been presented proving that all pipe materials are not equal. In every test of strength, durability, and dependability from cyclic loading and joint deflection to energy savings and tapping, Ductile Iron proves superior to pvc pipe.

The exorbitant costs associated with early replacement of underground piping make the engineer's initial choice of the best available piping material the most economical decision over the long term.

Ductile Iron pipe is a proven performer — a product with a performance history dating back more than 50 years — several centuries if its predecessor Cast Iron pipe is considered.

Ductile Iron pipe has the same stringent design and manufacturing standards for all sizes, not standards seemingly based more upon manufacturing efficiencies than user dependability and safety.

Design engineers and owners have traditionally considered Ductile Iron pipe the highest-quality piping material available. We believe this brochure points out some of the reasons Ductile Iron pipe has earned this reputation over the decades.

References

[1]ANSI/AWWA C150/A21.50-02, *AWWA Standard for the Thickness Design of Ductile Iron Pipe*, American Water Works Association, Denver, Colorado (2002).

[2]AWWA C900-97, *AWWA Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 in. through 12 in., for Water Distribution*, American Water Works Association, Denver, Colorado (1997).

[3]AWWA C900-07, *AWWA Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 in. through 12 in., for Water Distribution*, American Water Works Association, Denver, Colorado (2007).

[4]AWWA C905-97, *AWWA Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 in. through 48 in., for Water Transmission and Distribution*, American Water Works Association, Denver, Colorado (1997).

[5]Original tests were conducted by the Robert W. Hunt Company, an independent engineering testing firm, on 2/28/80 in Chicago. Additional tests were conducted at American Cast Iron Pipe Company in Birmingham on 3/21/90, 3/28/90, 4/4/90, and 2/20/91, and witnessed by Professional Service Industries, an independent consulting engineering firm.

[6]Robert T. Hucks, Jr., "Design of PVC Water-Distribution Pipe," *Civil Engineering*, June 1972, p. 73.

[7]ANSI/AWWA C151/A21.51-02, *American National Standard for Ductile Iron Pipe, Centrifugally Cast, for Water*, American Water Works Association, Denver, Colorado (2002).

[8]ANSI/AWWA C605-94, *AWWA Standard for Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe and Fittings For Water*, American Water Works Association, Denver, Colorado (1994).

[9]AWWA Manual M23, *PVC Pipe-Design and Installation, American Water Works Association*, Denver, Colorado (2002).

[10]ASTM D2412, "Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading," American Society for Testing and Materials, West Conshohocken, Pennsylvania (2002).

[11]ASTM D2152, "Standard Test Method for Adequacy of Fusion of Extrusion Poly(Vinyl Chloride) (PVC) Pipe and Molded Fittings by Acetone Immersion," American Society for Testing and Materials, West Conshohocken, Pennsylvania (1995).

[12]AWWA M23, p. 5.

[13]AWWA M23, p. 5.

[14]AWWA M23, p. 5.

[15]AWWA M23, p. 5.

[16]*Handbook of PVC Pipe Design and Construction*, Uni-Bell PVC Pipe Association, Dallas, Texas, 2001, p. 123.

[17]ASTM D2837 "Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials," American Society for Testing and Materials, West Conshohocken, Pennsylvania (2001).

[18]AWWA M23, p. 2.

[19]AWWA M23, p. 5.

[20]*Handbook of PVC Pipe Design and Construction*, p. 127.

[21]*Handbook of PVC Pipe Design and Construction*, p. 127.

[22]*Handbook of PVC Pipe Design and Construction*, p. 218.

[23]ANSI/AWWA C605-94, Section 5.3.

[24]*Handbook of PVC Pipe Design and Construction*, pp. 218-236.

[25]ASTM E23 "Standard Test Method for Notched Bar Impact Testing of Metallic Materials,"
American Society for Testing and Materials, West Conshohocken, Pennsylvania (2002).

[26]AWWA M23, p. 5.

[27]AWWA M23, p. 7.

[28]"Direct Tapping Comparison: Ductile Iron Pipe Versus Polyvinyl Chloride Pipe,"
Ductile Iron Pipe News, Fall/Winter 1987, pp. 8-11.

[29]*Handbook of PVC Pipe Design and Construction*, p. 414.

[30]AWWA M23, p. 99.

[31]*Blue Brute PVC Class Water Pipe Installation Guide*, Johns-Manville, Denver, Colorado, 1979.

[32]"Blackwood Flow Tests Prove Ductile Iron Pipe's Lower Head Loss," *Ductile Iron Pipe News*, Fall/Winter 1986, pp. 8-9. "Flow Tests Show Lower Head Loss for Ductile Iron Pipe," *Ductile Iron Pipe News*, Spring/Summer 1986, pp. 12-13. "Flow Tests Confirm the Superiority of Ductile Iron Pipe vs PVC," *Ductile Iron Pipe News*, Fall/Winter 1999, pp. 16-18.

[33]"Hydraulic Analysis of Ductile Iron Pipe," *Ductile Iron Pipe News*, Fall/Winter 1997, pp. 12-17.

[34]ANSI/AWWA C605-94, Section 2.2.

[35]ANSI/AWWA C600-99, *AWWA Standard for Installation of Ductile-Iron Water Mains and their Appurtenances*, Section 4.7, American Water Works Association, Denver, Colorado (1999).

[36]AWWA C900-97, Section 4.3.1 and AWWA C905-97, Section 4.3.1.

[37]ANSI/AWWA C605-94, Section 2.1.3.

[38]Hucks, p. 73.

[39]Hucks, p.72.

[40]AWWA M23, pp. 84-86.

[41]ANSI/AWWA C605-94, pp. 6-7.

[42]ANSI/AWWA C605-94, Figure 1.

[43]ANSI/AWWA C150/A21.50, Figure 1 and Table 2.

[44]AWWA M23, p. 34.

[45]AWWA M23, p. 34.

[46]AWWA C600-99, pp.12-13.

[47]*Ductile Iron Pipe Subaqueous Crossings*, Ductile Iron Pipe Research Association, Birmingham, Alabama, 2001.

[48]AWWA C605-94, p. 6.

[49]AWWA M23, p. 7.

[50]AWWA C605-94, p. 4.

[51]*Blue Brute PVC Class Water Pipe Installation Guide*, p. 7.

[52]T.M. Holsen, et al. "Contamination of Potable Water by Permeation of Plastic Pipe," *Journal AWWA*, August 1991, p. 56.

[53]"Some Town Water Supplies Threatened," News Release, Montana Department of Environmental Quality, March 17, 2000.

[54]T.M. Holsen, et al, p. 56.

[55]Approximately 621 U.S. and Canadian utilities are members of the Cast Iron Pipe Century Club for having Cast Iron pipe in continuous service for 100 years or more. At least 23 utilities have gained membership in the Cast Iron Pipe Sesquicentury Club for having Cast Iron pipe in continuous service for 150 years or more.

[56]E.C. Sears, "Comparison of the Soil Corrosion Resistance of Ductile Iron Pipe and Gray Cast Iron Pipe," *Materials Protection,* October 1968.

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PVC/10-08/4M
Published 1-92
Revised 10-08