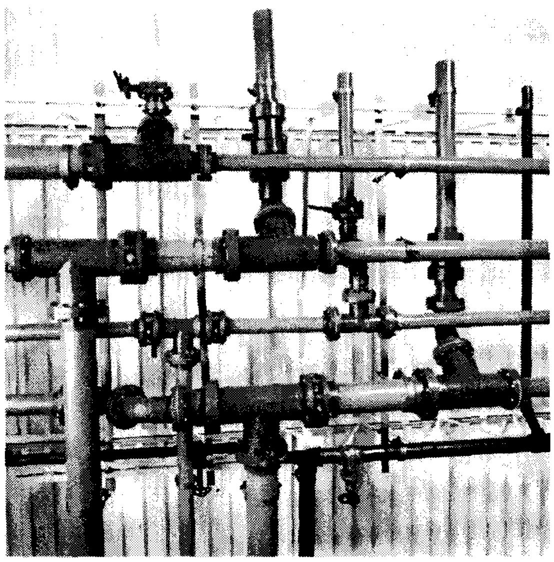
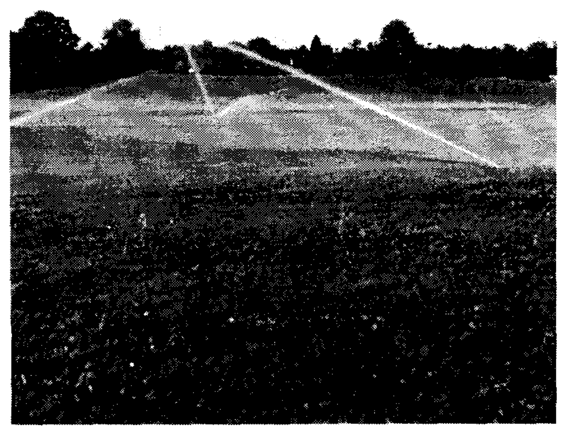
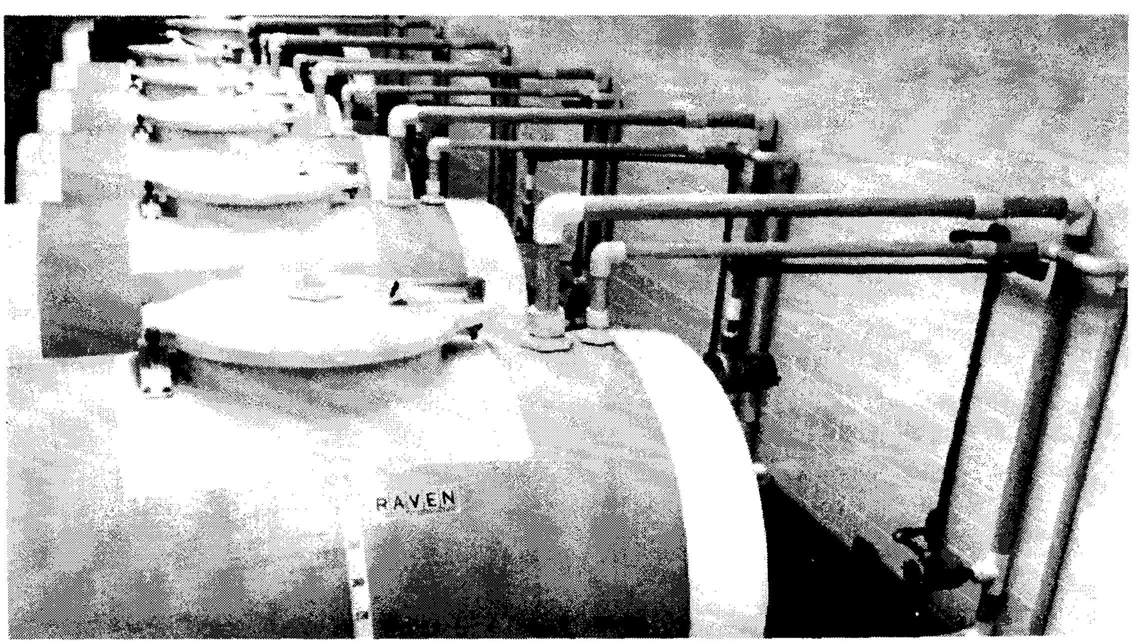
DESIGNING, OPERATING AND MAINTAINING PIPING SYSTEMS USING PVC FITTINGS

A Handbook of Design Guidelines and Precautions







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A Handbook of Design Guidelines
and Precautions

by

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Preface

This handbook has been prepared for use by PVC piping system designers, installers, operators and component manufacturers and suppliers to aid in understanding and eliminating typical problems that occur in today's systems.

The guidelines presented have been accumulated and developed from experience in evaluating system performance and troubleshooting problems with PVC piping systems in commercial, industrial and irrigation applications over the past 10 years. Many of the problems identified over these years are repetitious in nature, suggesting a lack of good guidelines to use in design, installation and maintenance.

In recent years, the PVC fitting industry has become concerned that their products were being used in applications without adequate design precautions and have noted considerable misunderstanding among designers, installers and operators concerning proper application and use. With the support and input of a number of PVC fitting manufacturers, this handbook has been prepared to address the problems that most frequently occur and to provide techniques to avoid these problems at the design, installation and operation phases of a project.

I wish to express my thanks to the PVC fitting manufacturers for their support and valuable technical input in the preparation of this handbook and to the Irrigation Association for its publication. I also wish to thank Dr. Jack Keller for providing valuable technical review.

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Introduction

The piping industry was revolutionized by the introduction, in the 1940s, of Poly(Vinyl Chloride) (PVC) pipe and fittings. Piping system components manufactured from PVC exhibit excellent corrosion resistance (PVC is inert to most acids, alkalies, fuels and other corrosives), are light weight, have a high strength-to-weight ratio, are exceptionally durable and have great resiliency. The use of PVC has grown steadily since its introduction, to the point where about 100,000 miles of PVC pipe is installed each year in North America alone. The growth of the industry has been due, in part, to the availability of a wider range of PVC pipe sizes and compatible fittings that are inexpensive and easy to install.

No portion of the piping industry has been affected by PVC pipe and fittings more than the irrigation industry. The large quantity of pipe and the numerous fittings required made PVC a natural choice. The relatively low cost of the materials, the ease of installation and the corrosion resistant nature of PVC have made PVC irrigation systems the heavy favorite for golf course installations, home and commercial installations and agricultural systems.

The revolution in piping materials has been followed closely in irrigation systems, especially golf course systems, by a revolution in sprinklers and control equipment. The advent of the valve-in-head sprinkler and computerized control systems in the last 10 years has provided nearly unlimited flexibility in system operation. In earlier golf course systems, the design consisted of the mainline system and lateral system, with a control valve separating the two. The pipe and fittings down stream of the control valve were pressurized only when that block was operating; they were vented to atmosphere through the sprinklers, so high surge pressures were unlikely. Also, the control systems were less sophisticated, with less flexibility, which meant that the flowrates in the system could be more easily balanced at design time, reducing the potential for high surges.

Today's systems are usually pressurized continuously. The control points in the systems are now at the sprinkler, subjecting all piping components in the system to maximum surges. The flexibility in control systems allows an operator to put water anywhere in the system every few minutes. Without adequate precautions, very high velocities can be generated, leading to high pressure surges. Also, the valve-in-head sprinklers often close quite rapidly, creating sudden changes in velocity at the sprinkler. Pressure surges due to valve closure have been measured at over 60 psi in valve-in-head systems and the potential exists for even higher surges.

Early irrigation systems were constructed mainly of steel pipe, especially in the smaller diameters. Sprinkler swing joint assemblies were nearly always constructed with steel components. From a pressure capacity standpoint, the components had strength well beyond the stresses put on them. With plastics, although the strength-to-weight ratio is fairly high, a given fitting or pipe used in an irrigation system is not nearly as strong as the steel counterpart it replaced. So at the same time that we have extra stresses placed on irrigation systems due to equipment changes, we have the introduction of components with less strength. This combination can lead to component failure unless careful consideration is given to design and operation.

In view of above considerations, the irrigation industry needs some guidelines in designing and operating irrigation systems with PVC components. With care in selection of components, in system design and operation, most of the problems can be eliminated. The following sections deal with aspects of PVC piping systems that are essential to satisfactory operation.

PVC Strength Characteristics and Typical PVC Fitting Failures

To better understand the performance of PVC fittings in piping systems it is helpful to examine the strength characteristics of PVC and the types of fitting failure that can occur. The types of failure fall into four main categories: 1) Burst failure; 2) Long term pressure failure; 3) Cyclic surge failure or fatigue; and 4) Mechanical failure due to external forces. Each of these types of failures will be discussed separately, although failure may be caused by a combination of situations.

PVC Strength Characteristics

Most PVC pipe and fittings used in the irrigation industry are manufactured from Type I, Grade I PVC compounds. Such a compound has a minimum tensile strength of 7,000 psi before being stressed and a modulus of elasticity in tension of 400,000 psi at 73°F. While the initial tensile strength of the compound is listed as 7,000 psi, this is based on a tensile test in which the loading rate is 0.20 inch/minute. On the other hand, the stress rating of the material is developed through long-term tests (at least 10,000 hours) on pipe under constant stress. The resulting longterm strength is divided by a safety factor of 2 to arrive at a 2,000 psi design strength.

The tensile strength of PVC under stress for an extended period of time is often described by a stress regression plot as shown in Figure 1. For example, in Figure 1, if a pipe is continuously stressed at 5,000 psi it would be subject to failing (bursting) after approximately 1,000 hours. The plot is based on results from the long-term tests on a substantial number of pipe specimens. The outside diameter and minimum wall thickness are determined for

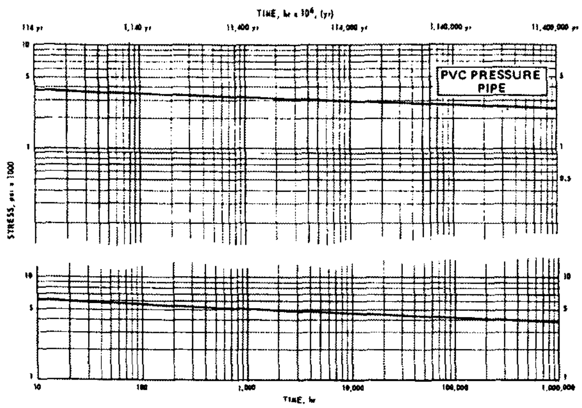

FIGURE 1. Typical stress versus time to failure regression curve for PVC pipe.

each specimen so that the hoop stress for each specimen can be calculated based on a test pressure. Each specimen is then subjected to the selected pressure (hoop stress) and the time to failure is recorded. Specimens subjected to highest stresses fail in the shortest time and those at lower stresses last longer. By this process, a whole series of stress regression data points are developed. These data are then analyzed in accordance with the ASTM D2837 method to select mathematically the "best fit" stress regression line. As can be seen in Figure 1, the time required to bring PVC pipe specimens to failure varies according to the pressure (stress) being applied: e.g., individual specimens should withstand 6,000 psi for 10 hours; or 5,000 psi for 60 days (1440 hrs); or 4,000 psi for 35 years (306,600 hrs); or 3,800 psi for 100 years (876,000 hrs).

These values are for static pressure conditions. Tests have shown that PVC pipe under continuous static pressure for a long period of time can be subjected to a quick burst pressure (less that 70 seconds in duration), and will perform essentially the same as pipe which has not been subjected to static pressure testing. It appears that, even after years of service, PVC pipe maintains its ability to withstand occasional high pressure surges.

However, if this pipe is subject to frequent pressure variations of a cyclic nature it can fail, even though the peak pressure never exceeds the design pressure of the pipe. The number of cycles to failure depends on the magnitude of the pressure variation. It appears that the ability of PVC pipe to withstand cyclic pressure conditions is independent of its ability to withstand constant static pressure. PVC pipe seems to have two "funds" upon which to draw, one labeled "static pressure life", and the other "cyclic pressure life".

It should be noted that the above conclusions are based on limited long term testing of PVC pipe. Based on these tests a design criterion considering cyclic pressure conditions has been developed and will be discussed later. As more testing is done, these phenomena will become better understood and the design techniques refined. Also, the reported cyclic testing to date has been performed mainly for pipe and not for fittings. From examination of PVC fittings removed from installations and tested, it appears that the above observations may not hold true for fittings. At least the number of cycles to failure may be considerably less, due to stress concentrations at points of direction change in the fittings.

Burst Failure

Burst failure in PVC pipe and fittings is usually rather dramatic. It may begin at a point of stress concentration or weakness and may continue by splitting through fittings and pipe for some distance. Typical examples of burst failure are shown in the photos in figures 2A and 2B. Sometimes, the failures will completely shatter a fitting and the adjacent pipe.

Burst failures usually occur during hydraulic transient conditions that create large pressure variations in the system. These include rapid valve closure, pumps starting or stopping, rapidly escaping entrapped air, or an air pocket shifting within a pipeline. Burst failure will, sometimes, occur in a pipe or fitting that was damaged during installation or that is subject to external loads. In these cases the failure may occur at pressures well below the expected burst limit of the product.

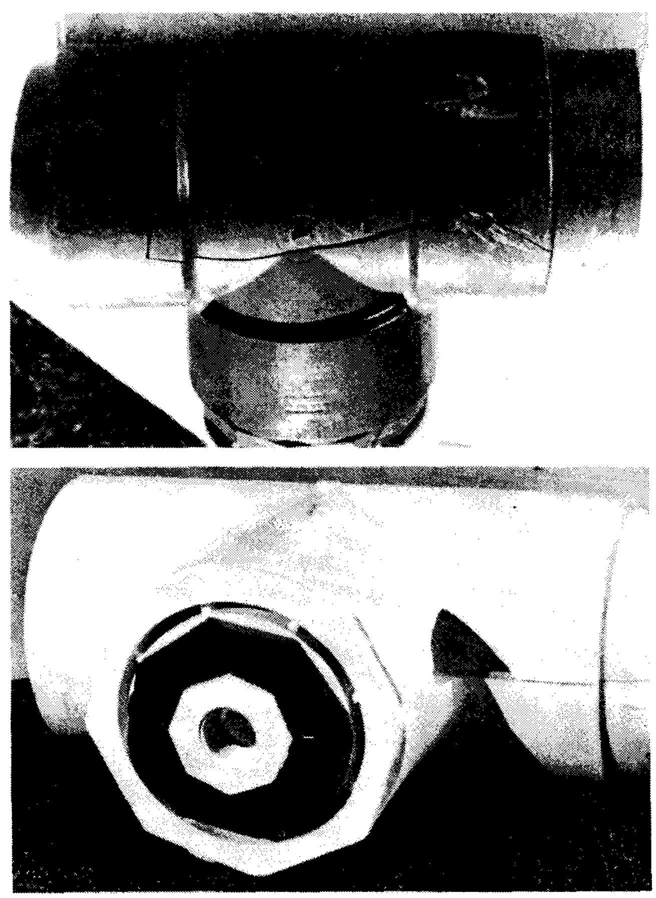

FIGURE 2A. Examples of typical burst failures in PVC fittings.

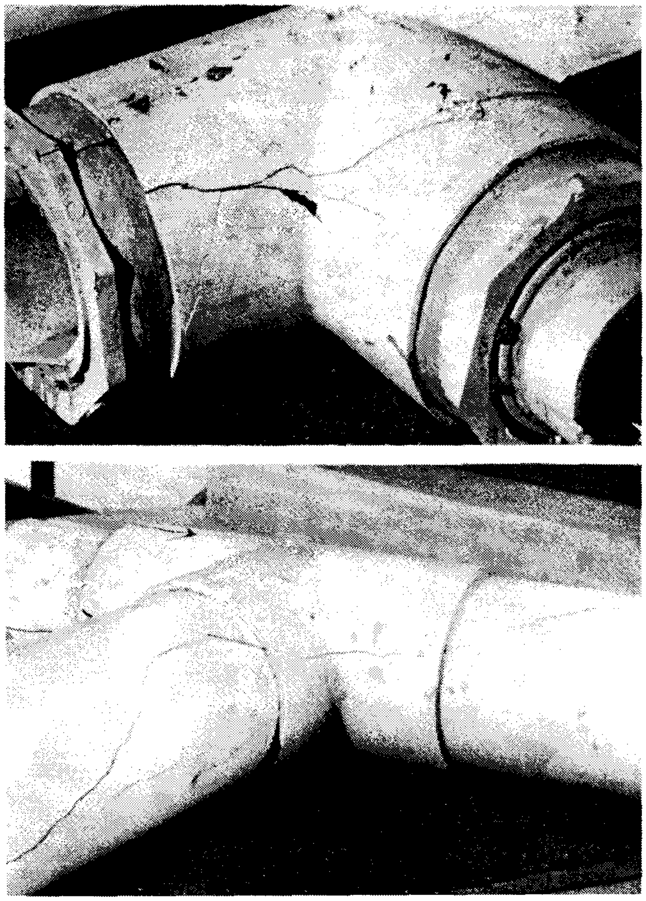

FIGURE 2B. Examples of typical burst failures in PVC fittings.

Long Term Pressure Failure

Long term pressure failure occurs when the system operates continually at a pressure that will eventually cause failure. The failures may occur within a short time after system installation or after many years. The failures will usually appear as slits or small cracks in the pipe or fitting along the minimum wall thickness or in an area of stress concentration. Some yielding of material will usually be evident.

Typical examples of what appear to be long term pressure failures in fittings appear in Figure 3. These examples had been installed in golf course systems for about 2 years when failure occurred. The systems were subject to relatively high (120 psi) operating pressures and significant cyclic pressure conditions. The failures seen may actually be a combination of cyclic and sustained pressure failure. It may be noted that these failures occurred at considerably lower pressures and fewer number of cycles than may be required to cause failure in Schedule 40 pipe. Note that, on one of the fittings, the material is eroded away around the fracture line. This is an indication that the crack was originally very small and that the leak went undetected for a sufficiently long period of time to allow the jet of water to churn the sand, which produces localized erosion on the outer surface of the fitting.

Cyclic Surge Failure

Cyclic surge failure can occur in systems that are subject to frequent changes in flow and/or pressure. Modern golf course systems with computer controllers are prime candidates for cyclic failure. A typical golf course system may experience from 40,000 to 100,000 cycles per year of magnitudes from 10 to 80 psi. H. W. Vinson (1) indicates that it is not uncommon to see cyclic failures in golf course systems after 2 to 5 years of operation. Typical examples of cyclic fitting failures appear in Figure 4. Note the similarity to the photos in Figure 3. It is very difficult to distinguish between cyclic failure and long term static failure in fittings.

Design standards have been proposed by H. W. Vinson (1) to consider cyclic surges. However, the standards apply to pipe and not fittings. It appears that fittings, due to the stress concentrations and extra forces placed on the fittings, will not withstand as many cycles, although their burst strength may be equal to that of the same class pipe. Limited testing completed by Keller-Bliesner Engineering

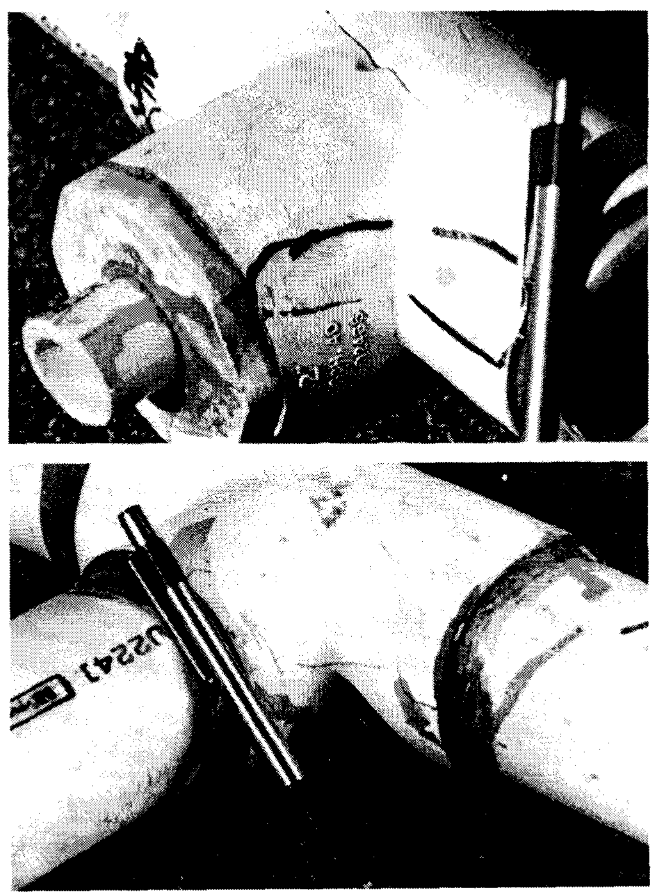

FIGURE 3. Examples of typical long term pressure failures in PVC fittings.

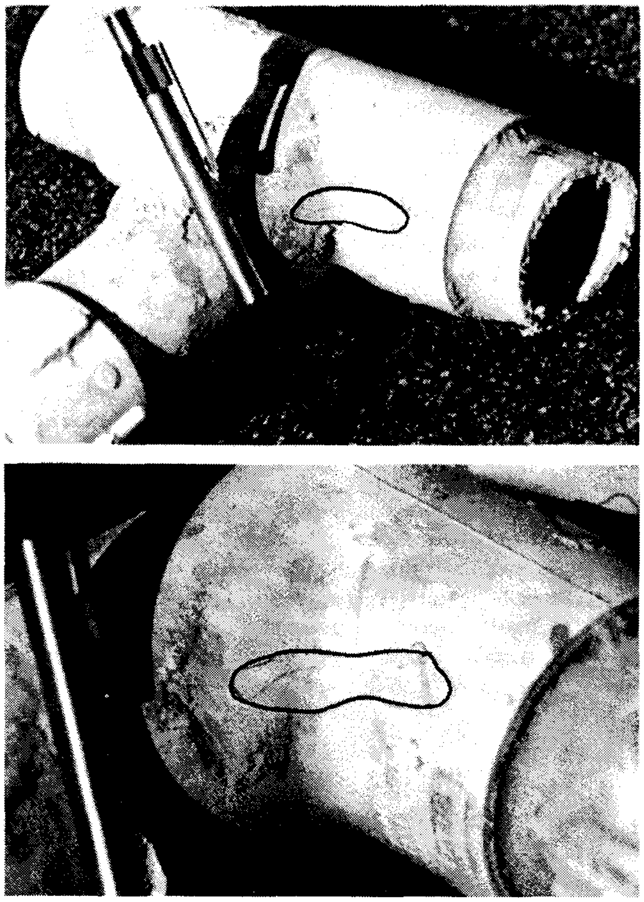

FIGURE 4. Examples of typical cyclic pressure failures in PVC fittings.

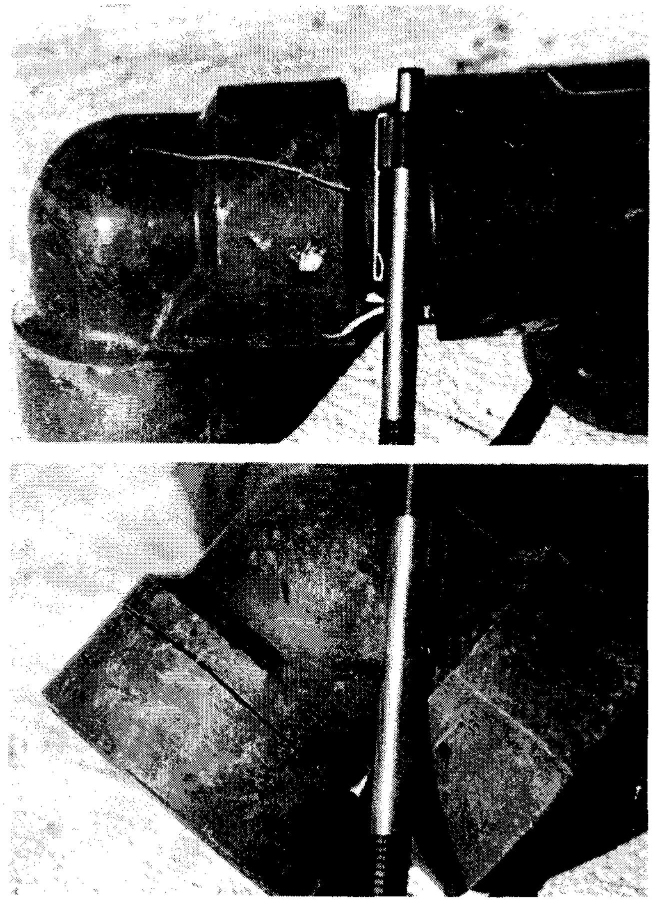

FIGURE 5. Examples of threaded PVC fitting failures due to over-tightening.

also indicates that there may be a marked reduction in burst strength after subjection to a period of cyclic pressure conditions. Used tees that had been subject to cyclic conditions sufficient to cause failure in some fittings were removed before failure and tested for burst strength against new fittings. The used tees exhibited only about 56% of the burst strength of the new tees. These test results are not all-inclusive due to a limited sample size and limited data on field conditions, but they do provide an indication that cyclic conditions may reduce the strength of PVC fittings.

Of all the operating conditions that can create problems, cyclic pressure appears to be the most critical, especially in golf course systems. Given the cyclic nature of irrigation system operation and their limited capacity to handle cyclic pressure conditions, fittings are the weakest system components. Serious consequences may result if this fact is not adequately considered at the design stage.

Mechanical Failure

"Mechanical failure" covers a multitude of piping failures that are unrelated to but may interact with the hydraulics of the system. One of the most common types of failure is splitting of female threaded fittings due to over-tightening. Since PVC is visco-elastic, it yields more easily on thread make-up than steel. The threads are also smoother and create less friction in make-up. It is therefore very easy to over-tighten PVC fittings. It is possible, with very little effort, to create circumferential stress beyond the failure limit when assembling threaded fittings. This is even more pronounced when using some thread lubricants, dopes or sealants. Figure 5 shows examples of failure of female threads due to overtightening. The failure usually appears as a split, perpendicular to the threads, beginning at the leading edge and extending into the body of the fitting. Occasionally, a split at the base of the female threads willappear parallel to the thread direction. This will usually occur in a fitting with a shoulder or thickened place near the base of the threads and is more common when the male part bottoms against a shoulder.

A second type of mechanical failure occurs when inadequate thrustblocking is provided. This allows excessive pressure to be placed on a fitting as the line pressure tries to displace it while the fitting is restrained by the pipe to which it is attached.

A third type of mechanical failure occurs due to improper solvent welding or improper fitting assembly. Figure 6 shows examples of these problems. Improper penetration

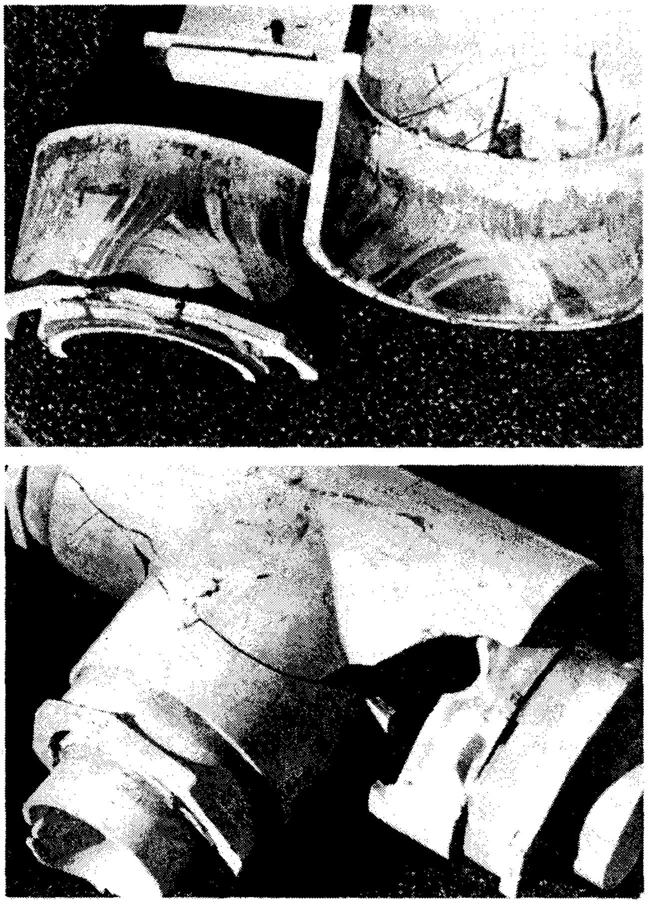

FIGURE 6. Examples of failure due to improper solvent welding of joints.

of pipe into socketed fittings significantly reduces the strength of the fitting. The tee and bushings shown in Figure 6 were assembled with only 50% socket penetration, significantly weakening the assembly. Improper solvent welding techniques can cause failures in the bonding, creating leaks or separation.

Another type of mechanical failure can occur due to temperature expansion. If sufficient expansion/contraction allowances are not made by providing expansion loops, offsets or slip joints, severe stress can be placed on the pipe and fittings.

PVC Fitting Standards— What They Mean and How To Use Them

Schedule 40 and 80 solvent weld and threaded fittings are covered by the following ASTM Standard Specifications:

D2464—Threaded Poly(Vinyl Chloride) (PVC) Plastic Pipe Fittings, Schedule 80.

D2466—Poly(Vinyl Chloride) (PVC) Plastic Pipe Fittings, Schedule 40.

D2467—Socket-Type Poly(Vinyl Chloride) (PVC) Plastic Pipe Fittings, Schedule 80.

These Standards deal mainly with workmanship, materials, dimensions, tolerances and testing. There are no pressure ratings for PVC fittings in these ASTM Standards. The only pressure references are for burst pressure. The standards even state that the burst pressures are used "only as an indication of quality" and "do not imply rated working pressures." The only information given that might indicate an attempt to construct a fitting for a particular pressure rating is that the Standard requires the minimum wall thickness of the fittings to be at least 125% of the wall thickness of the same Schedule pipe except in the sockets which are required to be 100% of the thickness of the same Schedule pipe. We believe this may be an insufficient increase in wall thickness to allow equal working pressures, even under ideal conditions. While we recognize that literally billions of PVC fitting are in use in a variety of applications, the problem with failures in some applications with no guidelines on working pressure suggests a need for better Standards that provide more information to the user concerning suitability for a particular application.

Table 1 presents the nominal and outside diameters, burst pressure and working pressure specifications of Schedule 40 and 80 PVC pipe. The burst pressures shown also apply to Schedule 40 and 80 solvent weld PVC fittings. The working pressures do not apply to fittings, however. No Standard exists that specifies a working pressure for fittings. In addition, no testing has been done to determine the working pressure of fittings manufactured to these specifications. Herein lies the problem of proper application of these fittings. Historically, most designers have assumed that a Schedule 40 or 80 fitting would perform equally with the same Schedule pipe or, worse yet, simply assumed that the term "Schedule" meant super heavy duty and they did not bother to check the test specifications.

TABLE 1. PVC Pipe Pressure Ratings—Schedule 40 and 80 (only burst pressures apply to fittings)*

		Schedule 40 specifications			Schedule 80 specifications		
Nominal Size	Outside Diameter	Wall Thickness	Burst Pressure (psi)	Pressure Rating (psi)	Wall Thickness	Burst Pressure (psi)	Pressure Rating (psi)
½	0.840	0.109	1910	596	0.147	2720	848
¾	1.050	0.113	1540	482	0.154	2200	688
1	1.315	0.133	1440	450	0.179	2020	630
1¼	1.660	0.140	1180	368	0.191	1660	520
1½	1.900	0.145	1060	330	0.2	1510	471
2	2.375	0.154	890	277	0.218	1290	404
2½	2.875	0.203	970	304	0.276	1360	425
3	3.500	0.216	840	263	0.3	1200	375
3½	4.000	0.226	770	240	0.318	1110	345
4	4.500	0.237	710	222	0.337	1040	324
5	5.563	0.258	620	195	0.375	930	289
6	6.625	0.280	560	177	0.432	890	279
8	8.625	0.322	500	155	0.5	790	246
10	10.750	0.365	450	141	0.593	750	234
12	12.750	0.406	420	132	0.687	730	228

*The same burst pressures apply to fittings but they carry *no pressure ratings*.

It may seem that, since fittings have the same burst pressure requirements as the equivalent pipe, the rated working pressures should be equal. Let's examine a fitting and see why this isn't the case. Figure 7 depicts a cross section of a typical 2 inch Schedule 40 tee. The straight side of the tee is stressed much like an equivalent length of pipe. However, the branch side of the tee is stressed much differently. In fact, a tee manufactured strictly to the ASTM Standard will be about 25% weaker on this side than an equivalent length of pipe if only the tee is considered (no strength derived from the inserted pipe). As the fitting is configured for standard ASTM testing, the branch side would only be about 10% weaker than equivalent pipe if it is assumed that the stress placed on the center of the fitting can be resisted by the fitting wall in the sockets. This is a fair assumption under quick burst conditions (less than 70 seconds) since the material that is overstressed has not had sufficient time to deform. However, under long term pressure conditions or cyclic conditions, the unsupported portion of the fitting will carry higher stresses and will tend to fatigue in these stress concentration areas. The failure locations shown on the tees in Figures 3 and 4 identify these stress concentration areas.

How, then, is a designer to decide how to use these fittings, if no pressure rating is given? That is the key question, and it cannot be answered with any degree of confidence until cyclic and long term tests are conducted and pressure standards developed. However, by analyzing the forces on the fitting, we can make some educated guesses and provide some general guidelines to use in the absence of pressure standards based on tests.

If the fitting received no additional strength from the pipe cemented into the sockets, then the highest expected pressure rating would be about 75% of that of the equivalent schedule pipe. Tests conducted on a limited number of 2 inch Schedule 40 PVC tees that had been subjected to conditions causing fatigue and/or sustained pressure failures in similar fittings in the same system burst at 56% of the pressure required to burst new fittings under burst test conditions. Using standard stress regression plots, the used fittings should have been capable of at least 70% of the original burst strength. The capacity of the fittings under cyclic conditions is not known, but appears to be significantly less than for equivalent Schedule pipe. For these reasons it is estimated that Schedule 40 and 80 PVC fittings should carry a pressure rating of not more that 60% of the rating for the equivalent Schedule PVC pipe. Table 2 lists these pressure ratings. It should be noted that these limits are based on very little hard data and should be used with caution. Certain circumstances may require even lower pressure ratings. It should also be noted that pressure ratings for Schedule 80 threaded pipe is 50% of the pressure rating for unthreaded pipe. Some further derating of Schedule 80 threaded fittings may be needed that is not reflected in the values in Table 2.

Some PVC fitting manufacturers are now offering or plan to offer higher strength tees and elbows that are reinforced with extra material in the stress concentration areas. These fittings exceed the thickness requirements of the current ASTM Standards and would normally be capable of with-

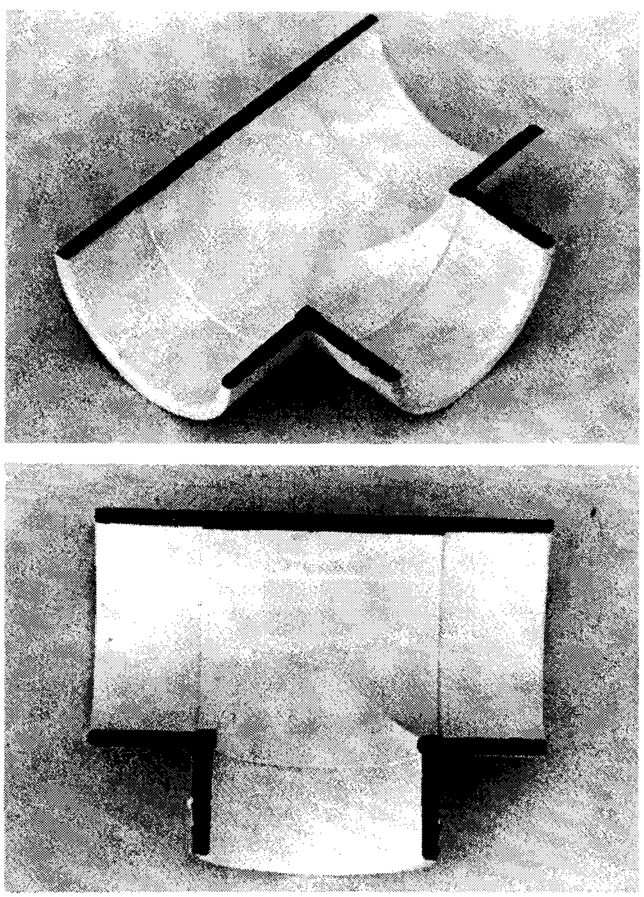

FIGURE 7. Cross section of a typical 2-inch Schedule 40 PVC tee.

TABLE 2. Suggested Maximum Working Pressures for Schedule 40 and Schedule 80 PVC Fittings. (Use as a general guide only. Actual allowable working pressures may vary widely with field conditions.)

	Schedule 40		Schedule 80	
Nominal Size	Burst Pressure	Working Pressure	Burst Pressure	Working Pressure
½	1910	358	2720	509
¾	1540	289	2200	413
1	1440	270	2020	378
1¼	1180	221	1660	312
1½	1060	198	1510	282
2	890	166	1290	243
2½	970	182	1360	255
3	840	158	1200	225
3½	770	144	1110	207
4	710	133	1040	194
5	620	117	930	173
6	560	106	890	167
8	500	93	790	148
10	450	84	750	140
12	420	79	730	137

standing greater pressures. However, no test results have been published and no new Standards set for these fittings. Also, there is some consideration in the industry to push for pressure rated solvent weld fittings. This approach would ease the difficulty of the designer in selecting the appropriate fittings.

Pressure Surges—What Causes Them and How To Control Them

Causes of Pressure Surges

Few piping systems are operated under "static" conditions for long periods of time. Hydraulic transient conditions or "surges" occur in every irrigation system. A pressure surge or "water hammer" is created any time the flowrate changes in a piping system. This may be caused by valve operation, pumps starting or stopping, line breaks, or rapid escape of entrapped air.

When a pipe contains a column of moving liquid, there is considerable kinetic energy stored in the liquid by virtue of its mass and velocity. If the velocity is suddenly decreased (by the quick closing of a valve) this energy cannot be absorbed by the liquid, since the liquid is nearly incompressible. It appears as an instantaneous shock to the pipe which may lead to excessively high pressures. This effect is greater as the pipe line is longer, the velocity change greater and the closing time of the valve shorter.

Instantaneous valve closure is often assumed in computing the maximum surge pressure per unit change in velocity. Table 3 indicates the maximum surge pressure for various PVC pipe sizes and SDR values for a range of velocity changes. These values can be used in design to estimate the pressure rating requirements of the piping system. Although the table shows values of velocity change up to 10 feet per second (fps), it is advisable to limit velocities to 5 fps to control maximum surges.

Controlling the Magnitude of Pressure Surges in the Design Phase

A number of design techniques are used to control water hammer in piping systems. To limit surges generated by pump operation, air chambers or surge tanks that absorb surges in conjunction with pressure regulating and pressure relief valves are often installed in the pumping station. Packaged pumping plants with all necessary controls and equipment are available from a number of manufacturers and are commonly used in golf course irrigation systems. When all valves and controls are properly sized and adjusted, surges generated by changes in pump flows and/or demands are reduced to non-harmful levels. If a packaged pumping plant is not used, the pump station should include, at the very least, a pressure regulating valve to maintain constant down stream pressure regardless of the flow rate. Pressure tanks decrease the pressure fluctuation seen at the valve and increase the pressure modulation in the system.

Controlled valve closure speed is critical in limiting the magnitude of pressure surges in the system. A typical valve-in-head sprinkler will close in 6 to 10 seconds, which seems sufficiently slow to limit surges to acceptable levels. However, the valves are electrically controlled hydraulic valves that operate on the principle of pressure difference across the valve for closure. The higher the pressure drop across the valve, the faster it closes. Therefore, the closer the valve is to being closed, the faster it closes, which

TABLE 3. Maximum pressure surge with instantaneous valve closure for water flowing in PVC pipe.

SDR	Pressure Wave Velocity ft/sec	Velocity Change—fps 1	2	3	4	5	6	<-not recommended-> 8	10
		Pressure Surge—psi							
13.5	1502	20.2	40.4	60.6	80.8	101.0	121.2	161.6	201.9
14	1474	19.8	39.6	59.4	79.2	99.1	118.9	158.5	198.1
17	1331	17.9	35.8	53.7	71.6	89.5	107.4	143.2	179.0
18	1292	17.4	34.8	52.1	69.5	86.9	104.3	139.0	173.8
21	1193	16.0	32.1	48.1	64.2	80.2	96.3	128.3	160.4
25	1091	14.7	29.3	44.0	58.7		88.0	117.3	146.7
26	1069	14.4	28.7	43.1		71.9	86.2	115.0	143.7
32.5	954	12.8	25.6	38.5	51.3	64.1	76.9	102.6	128.2
41	847	11.4	22.8	34.2	45.6	57.0	68.3	91.1	113.9

Table values based on the following equations:

$$a = 4660/(1 + k(DR-2)/e)^{1/2}$$
$$P = aV/2.31g$$

Where a = pressure wave velocity—fps
P = pressure surge—psi
k = bulk modulus of water = 300,000 psi
DR = Dimension ratio
e = modulus of elasticity for PVC pipe = 400,000 psi
V = change in velocity—fps
g = acceleration due to gravity—32.2 ft/sec^2

significantly reduces the effective closure time of the valve. As a rule of thumb, about 75% of the fluid flow is shut off in the last 25% of the poppet movement. Therefore, a 6 second closure time becomes a 1 1/4 second effective closure time. In general, valves with slower effective closure times generate smaller surges.

In simple systems, pressure relief valves downstream of the main pressure regulating valve can reduce the magnitude of some pressure surges. However, in complex systems, where surges can start at many places, it may be too costly to place pressure relief valves at sufficient intervals to be effective.

Entrapped air is one of the most troublesome and potentially dangerous causes of pressure surges. A later section will deal with the entrapped air problem.

At the design stage, the safest surge control technique is to limit velocities in the system to 5 fps and to include computation of surge potential in determining the pressure requirement of system components. Many problems will be eliminated if the surge potential is adequately assessed and the components of the system selected to withstand the potential surges.

The Effects of Management on Pressure Surges

As discussed earlier, given the flexibility of operation available with today's sophisticated irrigation controllers, all possible conditions cannot be foreseen at the design stage. Therefore, considerable care in management of the system is required. The magnitude of flow variations, and thereby velocity variations and potential pressure surges, of a typical golf course is depicted in Figure 8. Note the frequent changes in flow demand at the pump. Such variation is not uncommon in today's systems. With the shorter set times and repeated irrigations per set, the number of potential surges during the course of an operating season can exceed 40,000 mentioned earlier. The stress placed on irrigation systems by such fluctuation can reduce significantly the life of the system components, especially if the magnitude of the fluctuations is great and the pressure

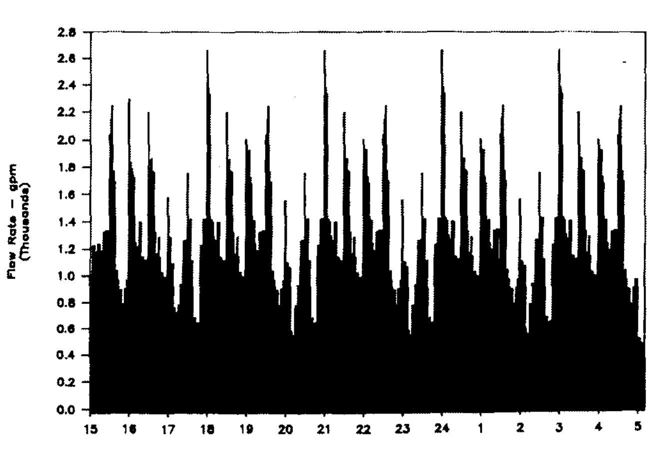

FIGURE 8. Typical flowrate variations at the pumping plant of a golf course system.

limit of the components is approached. Other locations in the system can have fluctuations even greater than those shown in Figure 8. It is not uncommon to have flow velocities in given pipe segments vary from zero to over 8.0 fps at 2 to 4 minute intervals unless the operating stations are carefully configured to balance flows.

To limit the magnitude and frequency of pressure surges, system operators should use the following guidelines:

1. Operate the system to maintain pump flowrate as uniformly as possible. This will not only reduce hydraulic transient problems but will increase the life of the pumping unit.
2. Attempt to balance system flows so the sprinkler set changes are systematic within system subunits. Avoid changing from one main area of the system and back again in the operating program. Maintain sub-unit flows uniformly, if possible.
3. Run fewer sets for longer times. Hydraulically, it is easier on the system to run a given set as long as possible, provided runoff does not occur, or the moisture holding capacity of the soil is not exceeded. This will allow for fewer sets and, thereby, fewer opportunities for surges to occur.
4. Avoid operating too many sprinklers in one area of the system and elevating the operating velocities. Use the design guidelines to govern the number of sprinklers that may operate simultaneously on a given pipe segment or loop.

The Dangers of Entrapped Air

Air entrapment in pressure pipelines is a much studied and discussed topic. Most designers are concerned about it, or should be, but many do not understand the full implications of the problem or the processes used to reduce the dangers associated with entrapped air. The problem of entrapped air is a complex issue. The behavior of air in a piping system is not easy to analyze, but the effects can be devastating.

Sources of Air in Pipelines

There are many potential sources for air in pipelines and the sources are usually multiple in any given system. The most likely source is entrapment of air during filling, either initially or when refilled after drainage. In some systems, air re-enters each time the pumps are shut off as the pipelines drain through low lying sprinklers or open valves.

Air is often introduced at the point where water enters the system. This is an especially common problem with gravity fed pipelines, but may occur with pumped systems as well. Even water pumped from deep wells may be subject to air entrance from cascading water in the well.

A less obvious source of air comes from the release of dissolved air in the water, due to changes in temperature and/or pressure. The quantities may be small in this case, but accumulations over time can create problems.

It is also common for air to enter through air release valves or vacuum breakers when the pressure drops below atmospheric pressure. This can occur during pump shutdown or during negative surges.

Why is Entrapped Air a Problem?

Air in a piping system tends to accumulate at high points during low flow or static conditions. As the flowrate increases, the air can be forced along the pipeline by the moving water and may become lodged at the more extreme high points where it reduces the area available for flow. Thus, these pockets of air cause flow restrictions which reduce the efficiency and performance of the system.

As an air pocket grows, the velocity past that point increases until eventually the air is swept on toward an outlet. While line restrictions are problems, a more serious situation can occur when air is rapidly vented from the system under pressure. Water is about 5 times more dense than air at 100 psi, so when a pocket of compressed air reaches an outlet, such as a sprinkler head, it escapes very rapidly. As it escapes, water rushes in to replace the void. When water reaches the opening, the velocity suddenly decreases, since air escapes about 5 times faster than water at 100 psi. The result is similar to instantaneous valve closure, except that the velocity change can far exceed the normal flow velocity in the pipeline. During tests at Colorado State University pressure surges up to 15 times the operating pressure have been recorded when entrapped air was rapidly vented under pressure. Such pressure surges can easily exceed the strength of the system components and even at lower magnitudes, repeated surges will weaken the system with time.

Dealing with Entrapped Air

Obviously, the best way to reduce problems caused by entrapped air would be to prevent it from entering the system. Precautions should be taken to eliminate air entrance. When systems are filled, either initially or after draining for winterization or repair, they should be filled slowly, at a velocity of 1.0 fps or less, and the air should be vented from the high points before the system is pressurized. Even with these precautions, some air can remain in the system.

To deal with this remaining air or newly admitted air, continuous-acting air relief valves should be installed at high points in the line and lines should be laid to grade wherever possible. Continuous-acting valves contain a float mechanism which allows the air to vent through a small orifice, even when the line is pressurized. The orifice diameter should be about 1 percent of the diameter of the pipe on which it is installed to allow the entrapped air to be slowly released.

Several combination air vent/vacuum relief valves are available for control of air in systems. Air and vacuum release valves are designed to exhaust large volumes of air from pipelines during the filling process and to close positively when water reaches them. These valves operate either by a buoyant float closing the valve as the water rises or by the impact of the water against a plate or other valve closure element. The valve remains closed until the pressure drops below atmospheric pressure, as would result from draining the line. These types of valves close rapidly and will cause a significant change in velocity at closure, thus care should be used in their sizing and placement.

Combination valves are manufactured to perform the functions of both continuous-acting and vent/vacuum air release valves. Upon filling, a large orifice is opened. Once water reaches the valve, the large orifice closes and allows air to escape only through the smaller orifice that is actuated by a float mechanism.

Pressure Pipe Design and Selection

The selection of the proper pressure rating of components of a piping system is a most important design consideration. Typically, the designer carefully determines the normal operating pressure range of the system, adds an appropriate value for expected surge, and selects components that are rated at this pressure or higher. Although for many applications this is an adequate approach, consideration should also be given to operating temperature and cyclic surges.

Pressure Rating

The ASTM pressure rating system for PVC pipe is based on a hydrostatic pressure design basis using a material strength of 4,000 psi and a safety factor of 2. Therefore, the pressure rating is computed on the basis of a design hoop stress, S = 2,000 psi. The pressure rating can then be computed by:

$$P = 2S/(SDR-1)$$

Where P = Hydrostatic pressure rating, psi
S = Design hoop stress, 2,000 psi
SDR = Standard dimension ratio
= Outside pipe diameter/ wall thickness

The above procedure does not apply to PVC fittings for reasons previously discussed. In the absence of better information on fitting pressure ratings, values from Table 2 can be used as a guide for Schedule 40 and 80 PVC fittings.

Temperature Considerations in Design

Most irrigation systems operate at water temperatures below 73 F. However, if higher fluid or ambient temperatures are expected, the pressure capacity of the PVC piping components should be reduced appropriately. Table 4 lists reduction factors for pressure ratings at elevated temperatures for various dimension ratios. To compute the pressure capacity at an elevated temperature for both fittings and pipe, multiply the standard pressure rating by the factors shown for the expected temperature.

TABLE 4. Pressure reduction factors for specific operating temperatures above 73° F.

Temperature	Reduction Factor* as a % of rated pressure at 73° F
up to 73°F	100%
80°F	90%
100°F	62%
120°F	39%
140°F	22%

*Use linear interpolation for intermediate temperatures.

Designing for Cyclic Surge Capacity

As noted earlier, cyclic surges are not adequately addressed by standard design techniques. In cases where total pressure variation due to cyclic surges equals or exceeds 50% of the working pressure, the potential for fatigue failure is significant. H.W. Vinson (1) has developed an empirical technique for computing the dimension ratio required to withstand cyclic surges in which the required design hoop stress is computed as follows:

$$S' = \left(\frac{5.05 \times 10^{21}}{C'}\right)^{0.204}$$

where S' = required design peak hoop stress, psi
C' = Anticipated number of cycles in the life of the system.

Having determined the required design peak hoop stress, the required dimension ratio for the pipe and fittings can now be calculated by:

$$DR = 2S'/P + 1$$

where S' = required design peak hoop stress, psi
P = peak internal pipe or fitting pressure (hydrostatic + surge),psi
DR = dimension ratio

Figure 9 graphically presents results of the above equations. This Figure may be used to select appropriate pressure ratings for PVC piping systems subject to cyclic surges.

To demonstrate the use of the equations, consider the following example:

Given:

PVC pipe—ASTM Standards
Golf course system—anticipated cycles—60 per day for 250 days per year
System life—50 years
Normal operating pressure—100 psi
Maximum expected velocity change during valve operation—4.0 fps

assume:

Instantaneous valve closure

Required:

Establish proper PVC pipe specification

Analysis:

The surge pressure from Table 3 (assume SDR 21) = 64 psi.

Thus, the peak internal pressure is:

$P = 100 + 64 = 164$ psi.

Furthermore, the expected number of cycles during the system's life is:

$C' = 60\text{/day} \times 250 \text{ days/year} \times 50 \text{ years} =$ 750,000 cycles

Thus, the peak hoop stress should not exceed:

$S' = (5.05 \times 10^{21}/750{,}000)^{0.204} = 1{,}694$ psi

and the required dimension ratio is:

$DR = 2 \times 1694/164 = 20.7$

Thus, SDR 21 pipe would be required. Fittings of equal pressure rating (200 psi) would also be required. From Table 3, fittings smaller than 2-inch could be Schedule 40, 2-inch through 4-inch fittings should be Schedule 80. Fittings larger than 4-inch should be pressure rated fittings capable of 200 psi working pressure.

An alternative method for determining the required DR is to use Figure 9. Entering Figure 9 with $C' = 7.5 \times 10^5$ and $P = 164$ psi gives a DR between 21 and 26, thus SDR 21 pipe should be used.

It may be noted that the Vinson equations used above are conservative. However, for extreme cyclic surge applications, such as golf courses, the added safety factor obtained by using these equations is justified.

Installation Considerations

One of the characteristics of PVC piping systems that makes them attractive is the ease of installation, due to

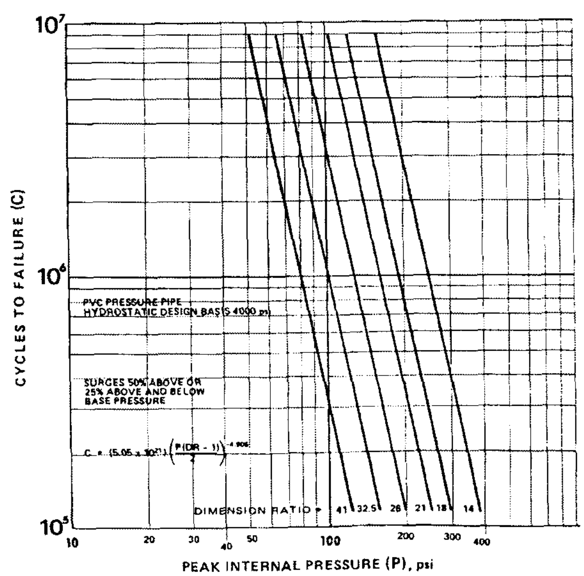

FIGURE 9. Cyclic fatigue life of PVC pipe when subjected to large pressure surges.

their light weight and ease of fabrication. However, precautions must be taken, as with other materials, in storing, handling, joining, laying, blocking, backfilling, filling and pressure testing.

Handling

Because of the light weight of PVC, there may be a temptation to handle it roughly. Care should be taken to avoid dropping pipe or fittings since undetected fractures could result, causing later problems. Also, physical damage to the pipe or fittings in terms of scratches or gouges may significantly reduce the long term strength of the component, especially under cyclic surge conditions. Special care should be taken in cold weather to avoid impact damage due to the increased brittleness of the material at reduced temperatures.

If pipe and fittings are going to be stored for extended time periods, they should be shielded from direct sunlight by some opaque covering, allowing air circulation around the components to avoid over-heating. Storage at high temperatures may cause some distortion of the components of the piping system and should be avoided.

Solvent Welding

Solvent weld joints require care during assembly. ASTM Standard D2855 should be followed, as well as any manufacturer's recommendations. Common problems associated with solvent cement joints are:

1. Inadequate primer or poor priming techniques which fail to provide sufficient glaze breaking and softening of the joining surfaces.
2. Improper application of cement, resulting in non-uniform coverage, e.g. dry places on either of the joining surfaces or puddling inside the joint.
3. Allowing the cement to become too dry before assembly, resulting in poor bonding.
4. Incomplete insertion of the spigot into the socket on assembly, reducing the solvent weld contact area.

If problems such these occur, inadequate bonding between the spigot and socket occur, which may lead to failure as shown in Figure 6. Although some force was required to separate the two surfaces, little fusing had taken place, indicating insufficient solvent penetration.

Threaded Fittings

With threaded steel piping the only problem pipe fitters needed to worry about was to make sure the threaded fitting didn't leak. To make sure, the joint was tightened a little more. With threaded PVC fittings, that technique can lead to fitting failure. The biggest single cause of failure in female threaded PVC fittings is over-tightening. This is easy to do because PVC threads are much smoother than the threads in iron pipe fittings and, with today's lubricating thread sealants, it is very easy to over-tighten a threaded PVC fitting. In addition, the PVC will deform more easily, allowing deeper thread makeup with less torque. In some cases, it is even possible to over-tighten the fittings by hand.

Arriving at a guideline for assembling threaded PVC fitting joints is difficult. The amount of torque required to assemble two fittings will vary with the thread taper and tolerance, the type of sealant used, the temperature, the size of the fitting, etc. The number of exposed threads is even less precise as a guide to proper assembly. The method that seems to work best is to first tighten the fittings "finger tight" and then add another 1 to 2 turns. Although "finger tight" is qualitative, it is a fair measure of the required initial tightness, and will rarely result in overtightened fittings. Tightening a fitting more than 2 turns past "finger tight" can exceed the design strength of the fitting. Figure 10 shows a plot of the number of turns past "finger tight" and the associated hoop stress generated in the female thread body. Two turns past finger tight for these 1½-inch fittings produced 2,000 psi hoop stress which is the standard design stress for PVC pressure pipe.

Much controversy exists over the type of thread sealant to use. Some manufacturers recommend a liquid or paste sealant and some recommend Teflon tape. As long as care is taken to follow manufacturers' recommendations, either can be used successfully. However, designers and installers should be aware of a few precautions for each type of sealant.

With paste or liquid thread sealants, extreme care must be used in selecting a sealant which is suitable for PVC pipe. Standard pipe dope and even some of the Teflon paste compounds are not compatible with PVC, so be certain that the sealant used has been tested and approved for PVC fittings. For fittings that will be subjected to movement, such as swing joint risers, the paste or liquid sealant must be non-setting. The higher viscosity sealants that do not dry seem to perform better in applications requiring movement.

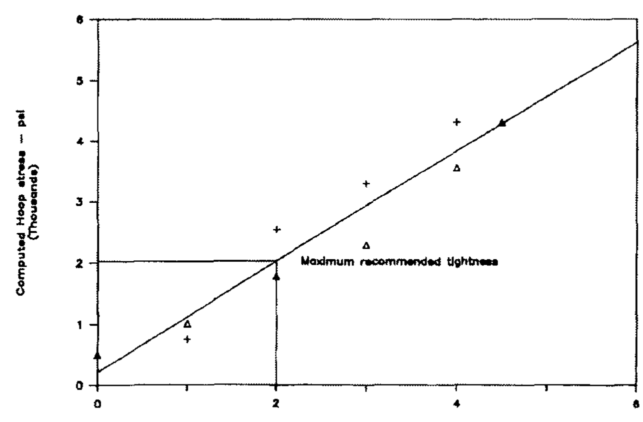

FIGURE 10. Relationship between hoop stress in the female thread and turns past finger tight in the makeup of 1½-inch threaded PVC fittings.

With Teflon tape, application is the primary precaution because the thickness of the tape varies widely among manufacturers. With very thin tape, multiple wraps may be required to achieve leak-free joints. However, when applying multiple wraps, the risk of thick and thin areas is increased. Such non-uniform application can cause additional stresses on the fittings. Uneven application can be avoided by using a tape that is at least as wide as the width of the threaded area on the fitting. (Take care to keep the tape from hanging over the end of the male threads as this excess tape can break loose and plug valves and screens.) Multiple wraps are made directly on top of the previous wrap without spiralling, creating a uniform thickness. Sufficient wraps (usually 2 to 5 depending on the tape thickness) should be used to insure that the threads do not "gall" or "lock-up" on make-up. A few test make-ups should be made as a trial. After make-up, the parts should be disassembled and inspected. The number of wraps should be adjusted until no evidence is seen of broken tape in the threads.

An additional precaution is necessary when handling threaded fittings. It is a fairly common practice to pre-assemble sprinkler swing joint assemblies and stock-pile them for later installation. If this is done, the assemblies should be kept in a shaded, ventilated storage area until installation. Excessive heat on the assembled fittings can cause the PVC to relax and loosen the fitting. Leakage may result, or, if the joints are re-tightened, the fittings could become over-stressed when cooled.

Thrust Blocking

Water under pressure exerts thrust forces in piping systems at: changes in pipe size or direction, dead ends, valves and hydrants. The size, shape and type of thrust blocking required depends on the maximum system pressure, pipe size, appurtenance size, type of fitting, line profile and soil type.

The design of thrust blocking requires knowledge of the thrust generated and the bearing strength of the soil against which the thrust block will be placed. Thrusts developed per 100 psi of line pressure for various pipe sizes and fitting types are presented in Table 5. These values can be used in conjunction with the soil bearing strength data presented in Table 6 to calculate thrust block sizes.

It is a fairly common practice to install thrust blocks at the locations discussed above. However, several precautions are necessary to assure that the thrust blocks are adequate. To be effective, a thrust block must: 1) be placed against undisturbed or fully compacted earth; 2) contact the fitting over a sufficiently large area so as not to create point stresses on the fitting; and 3) have sufficient area on the soil side to restrain the thrust without exceeding the bearing strength of the soil. Some typical examples of thrust block installations are shown in Figure 11.

To illustrate the technique for designing thrust blocks, consider the following example:

Given:

A 6-inch PVC 90 elbow operated at 100 psi maximum pressure is installed in a loam soil which is between a sand and a soft clay.

Analysis:

From Table 5, the thrust which must be supported by the soil equals 4,000 lbs.

From Table 6, the bearing strength of the soil is about 750 lbs/ft^2.

Therefore, the required thrust block contact area must be:

contact area = 4,000 / 750 = 5.3 square feet

Temperature Expansion Considerations

All pipe materials expand and contract with changes in temperature and this dimensional change must be considered in the design and installation of piping systems. As a general rule, a 10°F change in temperature will cause PVC pipe to expand or contract 3/8 in for every 100 ft of length. For example, a 1,000-foot pipeline installed in the summer when the ambient temperature is 90°F would shrink about 20 inches if the soil cooled to 40°F in the winter. This change in length must be accommodated or severe damage to the pipe and fittings will result.

There are several methods for dealing with thermal expansion and contraction. The most common today, especially for 4-inch or larger diameter pipe, is the use of gasket joints. A 3-inch or smaller diameter pipe can be

TABLE 5. Thrust developed per 100 psi of line pressure for various pipe sizes and fitting configurations.

Pipe Size (inch)	Fitting 90° Elbow (lbs. force)	Fitting 45° Elbow (lbs. force)	Valves, Tees Dead Ends (lbs. force)
1½	300	200	200
2	500	300	400
3	1,000		800
4	1,800	1,100	1,300
6	4,000	2,300	2,900
8	7,200	4,100	5,100
10	11,200	6,300	7,900
12	16,000	9,100	11,300

TABLE 6. Estimated bearing strength of typical soils

Soil Type	Bearing Strength Lbs/ft^2
Much, Peat, etc.	0
Soft Clay	500
Silt loam	750
Sand	1,000
Sand and gravel	1,500
Sand and Gravel with Clay	2,000
Sand and Gravel Cemented with Clay	4,000
Hard Pan	5,000

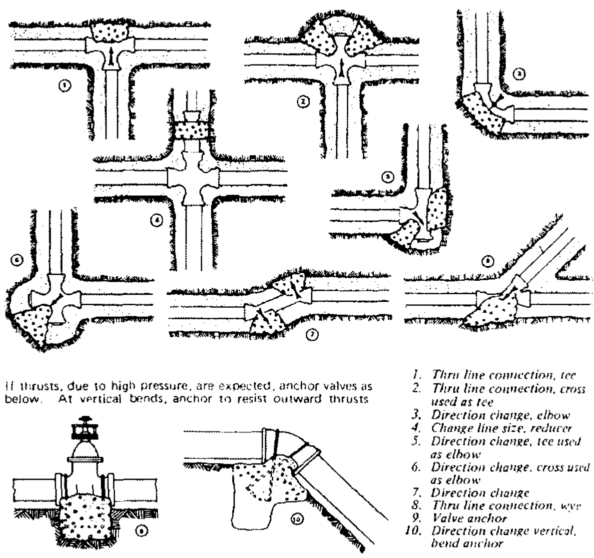

FIGURE 11. Typical thrust block installations.

snaked in the trench to accommodate the thermal expansion. For larger diameter pipe with solvent weld joints, periodic expansion joints, offsets or expansion loops must be used to accommodate the length change.

System Maintenance Requirements

Maintaining Air Relief and Surge Control Equipment

Automatic air relief and surge control equipment are only effective in limiting the magnitude of pressure surges when it is operating properly. In practice it is not uncommon to find an irrigation system with a number of the air vents closed or inoperable. Air vents, pressure relief valves, pressure regulation valves and surge tanks should be inspected and serviced at least annually to assure that they are operating properly. The small orifices on continuous-acting air relief valves can become plugged and may need frequent periodic cleaning. As with any mechanical device, periodic maintenance is necessary to maintain reliable operation.

Precautions in Winterizing the System

Systems that are not installed below the frost line must be drained during the winter. The most effective method of draining the system is to install the pipelines on grade with drain valves at the low points. However, with many golf course systems, the common method of removing the water from the lines is with high pressure—high volume air compressors. The water is literally blown from the pipes. This method is used since it is far less expensive than laying the many thousands of feet of pipe to grade and installing drains.

There are some inherent dangers in using compressed air to "blow out" pipelines. Remembering the discussion of air-induced pressure surges in pipe lines, the risk of high surge pressures is great if the water and air become mixed, or air pockets form within areas that are not totally drained. The velocities created can be very high and the surge potential is equally high.

If compressed air must be used to evacuate pipelines, considerable care should be exercised. A high volume compressor should be used, but the output pressure should be limited to less than 50% of the system operating pressure. If a sufficient volume of air can be developed at lower pressure, so much the better. Valves should first be opened in the low points and at distal ends of lines to drain tha larger diameter pipes and remove the majority of the water. Pressure should be limited to about 25 to 30% of the normal operating pressure during this phase. Once the major lines are evacuated, the close-in valves should be closed to allow evacuation of more distant segments. It will probably take two to three passes through the system, working from upstream to downstream to completely evacuate the water from all lines. A pressure gauge should be installed on the pipeline near the compressor and monitored continuously during the operation. Pressure should be built up slowly to allow the water columns to begin moving gradually, avoiding any sudden pressure surges. If the line pressure gauge fluctuates dramatically, the air pressure should be reduced to lower the risk of pipe damage.

Summary

PVC piping offers many advantages over other types of piping, especially to the irrigation industry. If the systems are carefully designed, installed and maintained, the piping will give years of satisfactory service. However, inadequate consideration of potential hydraulic situations, faulty installation, or improper operation can lead to significant problems, if not immediately, then at some time in the future. The cost of system failure is too great to ignore these potential problems, especially since moderate adjustments in system design can eliminate many of these problems. We hope that using the guidelines presented herein will aid designers and operators in meeting the rigorous demands placed on them. We also hope that additional performance testing can be accomplished on Schedule 40 and 80 fittings and that, ultimately, all PVC fittings can be pressure rated to eliminate the confusion that now exists in regard to their appropriate application.

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