PIPING

DETERMINING THE PROPER MATERIALS OF CONSTRUCTION FOR A LAB WATER SYSTEM

Picking the proper materials of construction for a lab water system is not as easy as one might think. There are a variety of questions that should be asked before simply placing the purchase order for the cheapest or even most popular material. Over specifying wastes capital money reserves, while under specifying could result in an inadequate system.

Since cost reasons often do not allow the use of the best-performing materials and not every application requires high-purity water, there are choices that fill the requirements for these other deionized (DI) arenas.

Most important, the primary purpose of the water supplying the lab should be addressed. Is the lab water supporting biotechnology or nanotechnology activities? Will drug synthesis or genetic research be involved? Will United States Pharmacopoeia (USP) water be needed? Are certain contaminants such as organic, ionic or metallic to be avoided?

The intended usage of the water should also be considered. Will it be used for cleaning, sample preparation, reagent or standards mixing, or manufacturing?

Lastly, how will the health of the DI water system be monitored? Will there be online controls such as measurement for conductivity, total organic carbon (TOC), silica, sodium and other parameters? Or, will outside lab services be necessary?

In researching the various materials of construction for lab water systems, the authors of this article decided to focus on the most common materials—polyvinyl chloride (PVC) and polypropylene (PP)—and to look at key things such as:

- Physical properties of the piping materials
- Additives for processing of the piping components
- Extractables of the "as supplied" product and the fabricated piping system
- Joining options, namely time, method, and contamination caused by joining
- Ability to modify system after commissioning
- Cost of material and installation

This study investigates the applicability of alternative polymer materials in the various DI water applications. Besides commercial aspects, it is especially focused on technical and performance aspects. Target applications for this report include the water used in hospital and university labs as well as some lesser demanding applications in the life sciences and electronics industries.

Background

A current topic is how to economize the constructing of a manufacturing facility. Because of economic constraints and cost reduction, the search for cheaper materials or lower installation costs is a common practice. However, among cost considerations should be the applicability of equal, or better performance as well as possible consequential costs such as increased maintenance, less lifetime, or costs for later disposal. Consequently, the main goal is to find the best compromise between cost considerations and best performance for a given application.

Physical properties. A comparison of physical properties is a great place to start, and offers a good source in assisting the enduser when selecting a piping system.

Additives. Additives will leach out of a piping system. This cannot be overlooked when deciding on a material of construction. Water is often referred to as the universal solvent, being able to dissolve acids and bases alike. DI water is especially aggressive and corrosive.

Extractables. In the past, leachout data for some PVC, specifically PVC clean materials have been published, but the tests were not always performed according to recognized test requirements. Also, the connecting technique by cementing was usually disregarded. Likewise, PP is only periodically consid-

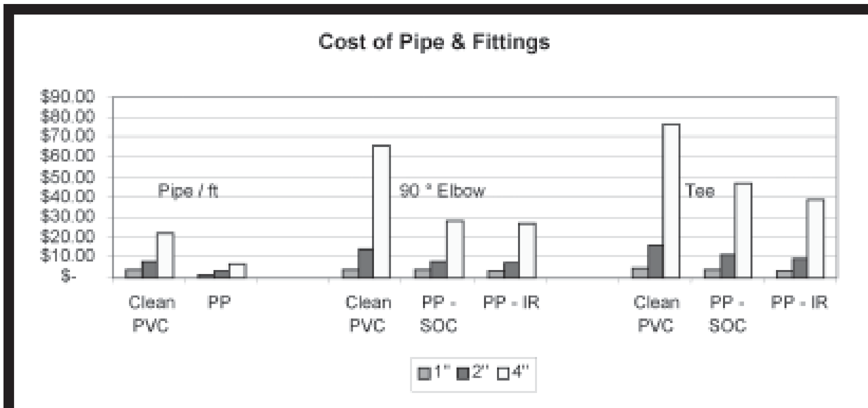

Figure 1. Pipes and fittings material costs.

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ered as an alternative. Therefore, the cleanliness portion of this study takes into account not only the leachout of components as supplied from the manufacturer, but also the influence of the connecting technique itself. That is, assembling a small piping system. Both PVC and PP materials were evaluated.

Joining options. For thermoplastics, you have two methods of joining the materials: heat fusion and solvent cementing. The advantages and disadvantages of each will be discussed later.

Ability to modify system after commissioning. Despite your best efforts in the design of the piping system, you will eventually need to modify or add to your existing system. You should consider what you will need to do and what your operational risks are in order to perform these modifications.

Cost of material and installation. The total cost of ownership dictates that you must consider the amount of time and the cost of the piping material in making a material choice that meets your needs.

Experimental/Performance Characteristics of Materials

Physical properties. Table A highlights key topics in material advantages and disadvantages. The table shows each material as it would be when freshly extruded in the pipe factory. Sources have witnessed degradation of PVC over time, though. One source reports the presumably aggressive nature of DI water itself on PVC. In this situation, an 8- to 10-year-old system of PVC conveying DI water shattered upon decommissioning and removal. The interior of the material was white and the PVC was overall very brittle. The system had been hydrogen peroxide sterilized upon commissioning (1).

Table A also lists surface roughnesses for materials. However, surface finishes (via scanning electron microscopy [SEM}) have been excluded from this report. The reason is that when the Semiconductor Equipment and Materials International (SEMI) taskforce for document F57 (2) came together, it was with the intent of correcting some outdated items in the existing SEMI E49 documents and creating a standalone document for piping system components. The taskforce had the objective to include within F57 what made sense to keep from E49, and to discard what

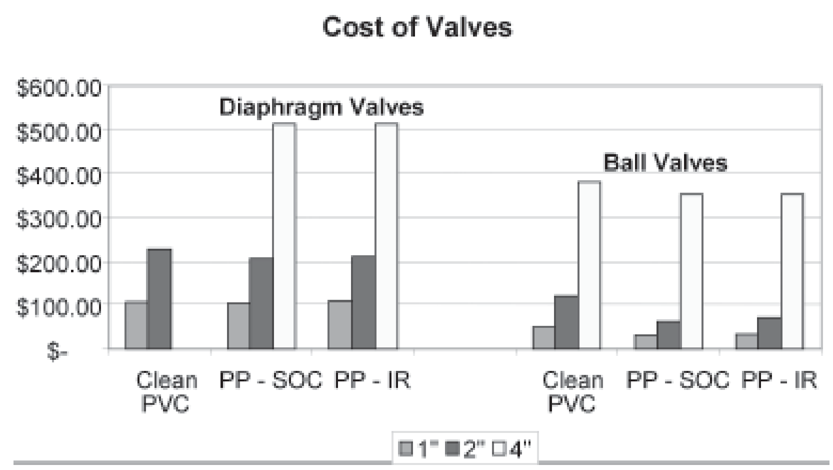

Figure 2. Cost of valves.

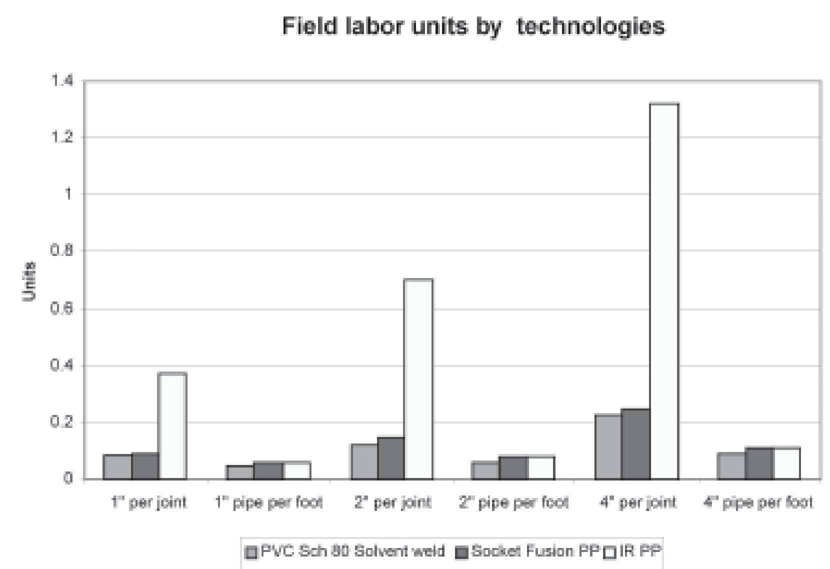

Figure 3. Material cost factors based on average project pricing.

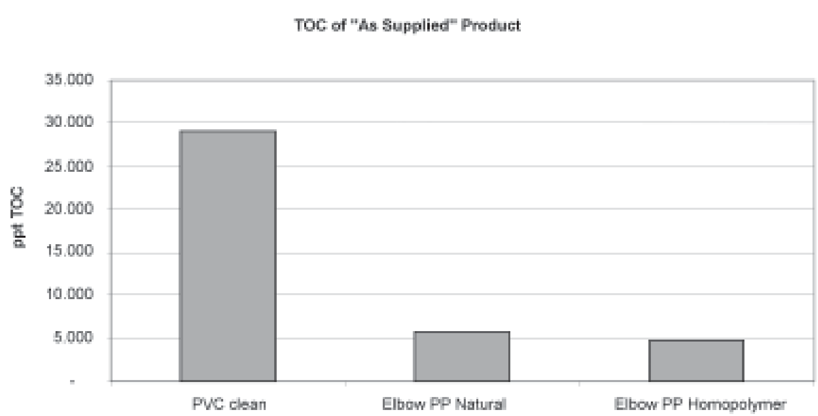

Figure 4. TOC leachout data of extractables from "as supplied" product.

TABLE A
Physical and Mechanical Properties

Measure	*PVC*	*Clean PVC*	*Natural PP*	*PP Homopolymer*
Tensile strength	7,500 psig @ 73°F	7,500 psig @ 73°F	3,600 psig @ 73°F	4,490 psig @ 73°F
Modulus of elasticity	430,000 psig	375,000 psig	130,500 psig	181,000 psig
Linear expansion	0.000028 per °F in/in	0.000043 per °F in/in	0.000053 per °F in/in	0.000053 per °F in/in
Impact strength	7 kJ/m^2 @ 73°F	12 kJ/m^2 @ 73°F	31 kJ/m^2 @ 73°F	85 kJ/m^2 @ 73°F
Max service temperature	140°F	122°F	176°F	176°F
Surface finish	not controlled	0.37 µm	0.80 µm	1.00 µm

should be omitted. The taskforce decided that while surface roughness (via contact profilometry) was worthwhile for the manufacturer to measure during production, surface finish (using SEM) was not. Subsequent balloting by the industry concurred with the taskforce recommendation. That is, not to include surface finish within SEMI F57.

Micrographs specified at 3500x presented problems to the analyst as they had trouble deciding what the morphology of this pipe is. Specifically, are darkened areas really micropores, or are they shadows and artifacts of the preparation technique? Are they raised areas or depressions?

Coupled with this, when one must consider that at this magnification the field of a typical micrograph represents less than 1/100000th of the surface area found in a single square centimeter of pipe.

Additives. Our study included a cleanliness pyramid where materials are qualitatively ranked from least to most clean, and also from those containing the most additives (e.g., PVC) to polyvinylidene fluoride (PVDF), which has no additives. It is widely known that PVDF has been the material of choice for high-purity water systems in the electronics industry for years (3) because it has the lowest contamination risk and other favorable factors.

Extractables. The cleanliness of PVC clean solvent cemented piping systems was compared to thermally welded systems[a] made of natural PP[b] and beta-nucleated PP homopolymer[c] that is cleaned and double bagged.

In assembling a system, elbows and pipes were constructed into a "piping system". Thus, the leachout of TOC, metals and anions, and the influence of the connection procedure itself were investigated. The PVC clean was solvent cemented, according to the manufacturer's instructions by using the glue recommended for high-purity applications. The natural PP[b] and the beta homopolymer PP[c] elbow-pipe-elbow systems were thermally welded[a], according to manufacturer's requirements. The glue to assemble the PVC clean system was included in this investigation as well.

To create a baseline the leachout for solvent cemented PVC clean or thermally welded natural and premium elbow-pipe-elbow systems were compared to "as supplied" elbows. That is, elbows delivered to us in the original manufacturer's packaging. Samples of 1-inch or 32-millimeter outside diameter products were obtained through normal distribution channels and in their original factory packaging. All test vehicles were statically leached.

Leachout tests were carried out according to the instructions given by SEMI F40-0699. (4) A leachout temperature of 60°C was used in this study because this is the maximum application temperature for PVC clean.

Following the prescribed 10 times prewash with 18.2 megohm-cm high-purity water to simulate the flushing process of a newly installed piping system, all items were leached for 7 days at 60°C.

Joining options. Here are some options for joining piping:

Solvent cementing. Chemical bonding is the process of joining articles made of thermoplastic resins by applying a solvent capable of softening the surfaces to be joined, and pressing the softened surfaces together. Adhesion is attained by means of evaporation of the solvent, absorption of the solvent into adjacent material, and/or polymerization of the solvent cement

Thermo fusion involves the introduction of applying heat to the joining surfaces, then joining them under pressure to effect a weld. Butt-fusion welding[d] has the cleanliness advantage in that it is a non-contact process. The heater head never touches the pipe.

Bead-and-crevice-free consists of transmitting precisely defined thermal energy to the pipe and fitting by means of half-shell heating elements that encircle the joint. At the same time, an elastic, gas-pressurized bladder is positioned inside the securely clamped pipe and fitting to prevent formation of fusion bead.

A summary of the steps required to perform a fusion is found in Table B.

Ability to modify system after commissioning. Tables C and D list the modification capabilities and set times of each material.

Cost of material and installation. Figures 1 through 3 are offered to help the reader understand the total costs of each system. The examples are in either units or percent difference to allow for regional variations in costing.

Discussion and Summary

Physical properties. As can see from Table A, PP has advantages in high and low temperature capabilities and far superior impact capabilities. It is also a much more ductile material that will limit any problems to a small area. The additional additives in PVC give it an advantage in ultraviolet (UV) resistance. As stated previously and witnessed by others, these additives can come out of the pipe wall and dramatically change the physical properties of the material.

Additives. Solvent introduction into a high-purity water stream, via solvent cement for joining or from additives, provides an excellent nutrient source for microbial growth. Technical literature states a positive correlation between TOC concentrations and viable bacterial numbers. (5) Additionally, one source states that "Microbial contamination in analytical-grade water can negatively affect the results of critical laboratory research" (6).

Extractables. Figures 4 through 6 show the TOC, chloride and fluoride, and remaining anions, respectively, for the "as-supplied" elbow. Figure 7 represents the TOC leachout data for the "system" (fabricated piping system product).

The SEMI F040 methodology uses a static leachout procedure whereby the component to be tested is pre-washed to simulate flushing after installation, and then exposed to high-purity water for 7 days at an elevated temperature. Finally, the high-purity water is analyzed for the contaminants that have gone into solution.

The reasons for using SEMI static test methods and such high temperature testing when the actual usage of the material might be much lower is a result of years of debate in the high-purity industry, and optimization by a team of industry partners, suppliers, and chemists. The procedure has been optimized to give a reliable result in a short period of time (7 days, only 1 preparation step). The high temperature supports the leachout of contaminants so that the time could be limited to 7 days. These static and accelerated tests speed the leaching process that will eventually happen over time.

The goal of this SEMI standard was to develop a reproducible and reliable routine procedure to assess the contamination hazard for high-purity water and liquid distribution systems because of the leachout of piping system material only, and the independence of extraneous equipment. Dynamic tests depend too much on the test set up and parameters used (e.g., flowrate, component diameter, and others). Dynamic values (micrograms per liter [μg/L] and nanograms per L [ng/L]) are useful ways of maintaining control over process fluid purity within the manufacturing environment. However, for processes sensitive to atomic or trace molecular level impurities, dynamic values fail to show the true picture of the contamination present and are often 7 orders of magnitude less sensitive than the values that are derived from a static test (μg/ per square meter [m^2] and ng/m^2). Nevertheless, for the benefit of the reader we have applied the theoretical dynamic concentration (TDC) as allowed by SEMI F57 to display our data in parts-per-trillion (ppt), as though there were dynamic flowing stream tests.

TABLE B
Summary of Steps

Solvent Cementing	*Socket Fusion*	*IRâ Butt Fusion*
1 – Cut pipe	1-cut pipe	1- cut pipe
2 – Debur pipe	2- champer pipe	2- face pipe
3 – Dry fit joint	3- clean	3- clean
4 – Prime the joint	4- heat	4- add heat
5 – Apply cement	5- join	5- join
6 – Join pipe/fitting	6- QC	6- cool down
7 – QC - cleanup		7 – QC
Initial set time	*Initial set time*	*Initial set time*
5 – 120 Min	*< 1 Min*	*2 ½– 9 Min*

Note: Set time is the amount of time you must wait until you can move the joint. All times are based on ½-in to 4-in joints at 60° F.

Total organic carbon. The PVC clean elbows (as supplied from the manufacturer) were approximately 5 to 6 times higher for TOC than the values found in the natural PP[b] and beta PP homopolymer[c] (see Figure 4).

Figure 7 also represents the TOC leachout results of the elbow-pipe-elbow assembly. This arrangement encompasses the component as well as the connection technique. In the case of the PVC clean, most likely the glue is contributing a large TOC amount because the leachout has increased about 10 times for solvent-cemented parts in comparison to the original supplied unconnected parts. On the contrary, the thermally welded[a] materials[b, c] did not appear to change in TOC level. The assumption that the glue is the main reason for the increasing TOC levels can be proved by analysis of the glue components. The glue consists mainly of organic ingredients, which are predominantly or partly soluble in water.

Anions. The most remarkable differences for anions are shown in the fluoride, chloride and sulfate results (see Figures 5 and 6). The fluoride values for the studied elbows of PVC clean were more that 100 times greater than the other materials[b, c]. As expected, the chloride leachout for the PVC clean was almost 1,000 times higher than either PP types. When an "as-supplied" elbow is compared to the constructed "system", a dramatic jump in chloride was observed in the glued PVC clean.

Solvent cement. When considering the influence of the welding procedure, the most important problem with a solvent-cemented system is, of course, the glue. The glue consists mainly of tetrahydrofurane (THF), and other organic solvents. This involves a high risk of TOC contamination. A variety of other potential contaminants can also come from the ingredients of the glue, such as solids and ash, which are typically PVC stabilizers, modifiers, and thickening agents. The ash usually consists mainly of silica (SiO_2). Table E shows the components found in the various joining technologies and highlights some glue ingredients found during our analysis.

Joining options. Heat fusion offers a distinct advantage by having of the shortest time before moving the joint as well as the ability to test the system right after the completion of the fusion.

Ability to modify system after commissioning. Likewise, the downtime realized when modifying a system and waiting before testing can be excessive in glued systems. Brittle material may also shatter or chip when being cut for modifications.

Cost of material and installation. When you take material cost (Figures 1 through 3), cost of cement, labor and the rinse up time, it becomes apparent that the PP systems with the additional cost of the machine is still an option to consider.

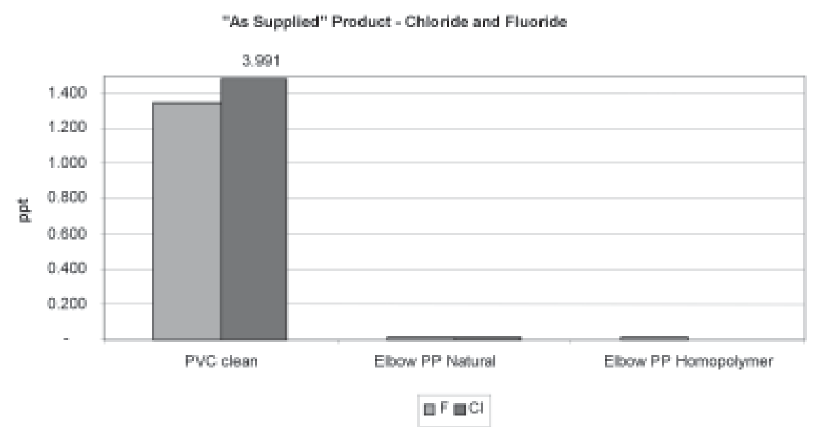

Figure 5. Chloride and fluoride leachout data extractables from an "as supplied" product.

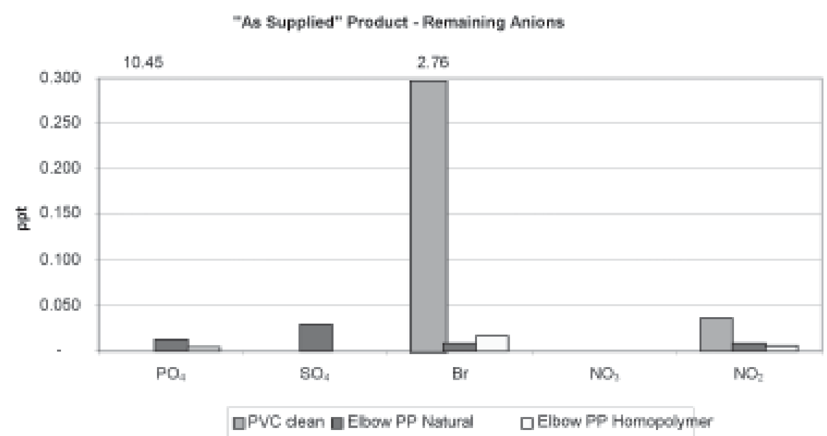

Figure 6. Remaining ions leachout data showing extractables of "as supplied" product.

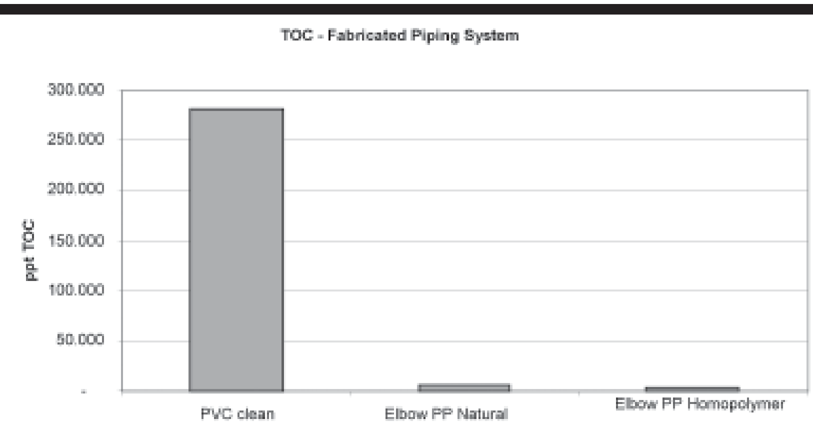

Figure 7. TOC leachout data of extractables from a fabricated piping system product.

Conclusions

When one begins the decision process for installing a piping system, many factors, as the authors have outlined, must be considered. Each material has its advantages in terms of initial physical properties, but longevity cannot be derived from knowing tensile and impact strengths. Experience is often the best source for such information.

Additives are known to come out of piping system walls. Sometimes they present themselves as detectable contaminants in the DI water system, sometimes as nutrients for microbes. However, the additives serve a purpose within the material. If they are removed then the material characteristics change.

No proper extractable procedure exists which gives reliable and comparable results when considering lower temperature materials like PVC. We used SEMI F040 as a means to perform a fair comparison.

The higher concentrations of TOC seen in the solvent cemented system (PVC clean) are possibly caused by water solubility of the cement. This hypothesis is supported by the fact that with the thermal welding systems[a], no TOC increase could be seen in either the PP samples[b, c]. The glue needs these organic ingredients to archive the properties that are necessary to cement the pipes together. One source quotes the effect of increased TOC from glue lasting for 1 to 2 months in running streams. (7)

Although PVC is used in a number of applications within the life science industry, one source states that PVC piping cannot be used for pharmaceutical water in accordance with *USP 26*, since no single supplier can provide USP and U.S. Food and Drug Administration (FDA) conformance for the glue. Further, the FDA states that a sanitary design is required. The joining technology, valve, and fitting configurations in PVC are not made for a sanitary design. Additionally, the guidelines such as found in International Society of Pharmaceutical Engineers (ISPE) guidelines clearly state that PVC is not suitable for USP grade water because of higher leach out of TOC, and sanitization restrictions (8).

Clean joining techniques, including the absence of TOC, can only be found in thermally welded systems. Additionally, thermal welding offers the advantage of less time before testing and a lower overall total cost of ownership.

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TABLE C
Modification Capabilities

	Solvent Cement	*Socket Fusion*	*Thermal Fusion*	*Beadless Fusion*
Field (in place) Joining	yes	yes	yes	possibly
Time before testing	.25 – 72 hours	0 – 1 hours	0 – 1 hours	0 – 1 hours
Contamination of system	high	low to none	low to none	low to none
Special equipment	no	yes	yes	yes

TABLE D
Set Times – Dependant on Ambient Installation Temperatures

0º - 40ºF	*Set Times in Minutes*		
Size range	*Solvent Cement*	*IRâ Fusion*	*Socket Fusion*
1/2 - 1-1/4	10	5.5	5
1-1/2 - 2	15	5.5	5
2-1/2 - 4	720	5.5	5
40º - 60ºF	*Set Times in Minutes*		
Size range	*Solvent Cement*	*IRâ Fusion*	*Socket Fusion*
1/2 - 1-1/4	5	5.5	2
1-1/2 - 2	8	5.5	2
2-1/2 - 4	120	5.5	2
60º - 100º F	*Set Times in Minutes*		
Size range	*Solvent Cement*	*IRâ Fusion*	*Socket Fusion*
1/2 - 1-1/4	2	5.5	2
1-1/2 - 2	3	5.5	2
2-1/2 - 4	30	5.5	2

TABLE E
Components Found in the Joining Technology

Components Found in the Joining Technology	*Homopolymer PP*	*Natural PP*	*Typical Glues* Stated Values*	*PVC clean Measured Values*
Tetrahydrofuran	N/A	N/A	20-50%	52.7%
Methyl ethyl ketone	N/A	N/A	5-40%	32.7%
Cyclohexanone	N/A	N/A	10-30%	<0.1%
Solid content	N/A	N/A	10-25%	14.6%
Ash	N/A	N/A	1-3%	<0.1
Container “open time” (minutes)	N/A	N/A	4	2

Notes: Container Open Time is important due to the volatility of the solvents. The longer the lid is off the more the chemical composition of the solvent cement changes due to the flashing off of the solvents
N/A = not applicable

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Endnotes

[a]IR$^{â?}$ is a thermal welding technique of Georg Fischer Piping Systems in Tustin, Calif.
[b]The article refers to PROGEFâ? Natural polypropylene from Georg Fischer Piping Systems in Tustin, Calif.
[c]The double-bagged PP homopolymer referred to in the article is known by the trade name of PROGEF^{â}? Plus.
[d]The butt-fusion technique from Georg Fischer Piping Systems is known as IRâ-Butt Fusion.

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