

Testing Components Used in Semiconductor Liquid-Handling Systems to Assure Product Purity and Reliability

Donald C. Grant, Dennis Chilcote, Wayne Kelly, and Mark R. Litchy
CT Associates, Inc.
Bloomington, Minnesota

Allen Rodemeyer, Dave Henderson, and Kenji Kingsford
Saint-Gobain Performance Plastics
Garden Grove, California

Abstract

While the need for ultraclean semiconductor manufacturing equipment has long been clear, cleanliness guidelines for manufacturers who produce the equipment have been slow in coming. While waiting for SEMI specifications, a few manufacturers have set their own goals and testing procedures. St.-Gobain Performance Plastics (SGPPL) has adopted a testing program for particle purity, metallic extractables, and reliability of its components used in high-purity applications. Components are tested for particle shedding into flowing ultrapure water. Active components are also tested during operation. The DyconE^{x SM} dynamic extraction procedure is used to determine the rate of metal extraction over time. Data from this test can be used to predict a component's contribution to metallic contamination in a process chemical stream. The reliability of components is tested under operating conditions in both 37% HCl and 49% HF, because they typically cause different types of failures. To allow statistical analysis of failure, tests are continued until 70% or more of the components have failed. The testing program has shown that most of SGPPL's components already meet their goals.

Introduction

The processes used to produce state-of-the-art semiconductors are extremely sensitive to contamination. To reduce yield losses due to contamination, semiconductor manufacturers have imposed strict purity requirements on equipment manufacturers. As microcircuits increase in complexity and their features decrease in size, the need for purity will continue to increase. In addition, failure of process equipment results in costly fab downtime. For these reasons, manufacturers of semiconductor equipment are continually searching for system components that are very clean and highly reliable.

Equipment components can add three types of contaminants to microcircuit production processes: particles, metals, and organics. Particulate contamination can cause open or short circuits, structural defects, altered electrical properties, and unreliable photolithographic reproduction. Metallic contaminants on the semiconductor surface can diffuse into the substrate during subsequent heat treatments, causing drifts in surface potential, current leakage, and structural defects in vapor-grown epitaxial layers, and reduced breakdown voltage of gate oxides. Problems caused by organic contamination are less well understood.

SEMI is in the process of writing specifications for particulate and metallic contamination in components [1]. The process is complex because it requires the concomitant development of testing and analysis methodologies. As the SEMI specifications are being developed, some companies have set their own specifications for their products and components. For example, BOC Edwards (BOCE) has set specifications for metal extraction and particle release from all components used in its chemical delivery systems. BOCE systems must not contribute more than 20% of the metallic contaminant concentrations allowed by the Semiconductor Industry Association roadmap [2] for process chemicals. Systems specifications are normalized for surface area so that the contamination limit for individual components can be calculated [3]. Present component purity specifications for surface extraction and bulk extraction rate are $\leq 20 \text{ ng/cm}^2$ and $\leq 0.5 \text{ ng/cm}^2\text{-day}$ after 7 days of exposure to chemical. Component testing should be performed in 35-37% HCl, 49% HF or 70% HNO₃ because these chemicals aggressively extract any metals present in polymers [4].

BOCE has also set specifications for particle release from components. They must release $< 2 \text{ particles/mL/m}^2$ ($\geq 0.1 \mu\text{m}$) within 1,000 liters of flushing. Active components, those with moving parts, are exempt from this specification if they add $< 0.1 \text{ particle/mL}$ ($\geq 0.1 \mu\text{m}$) to water flowing through the component within 300 liters of flushing. Active components must meet a second specification limiting particle release during operation. For example, valves must release $< 100 \text{ particles}$ ($\geq 0.1 \mu\text{m}$) per actuation cycle within 500 cycles. The procedures and acceptance criteria for other types of active components are being determined.

Another major concern for equipment manufacturers is reliability of components. The production of integrated circuits often requires the use of harsh chemicals. Expectations about reliability are often not met because a component's resistance to damage varies from chemical to chemical. To ensure reliability in the field, reliability tests should be conducted under worst-case conditions.

Selection of worst-case test conditions requires an understanding of a component's failure mechanisms. For example, diaphragm valves have two main modes of failure. Internal metal components such as springs most likely fail because of metal corrosion. Corrosion can be caused by acids that permeate the valve diaphragm. HCl is thought to be the worst chemical environment for this type of failure. The other major failure mode is diaphragm fatigue, possibly exacerbated by environmental stress cracking (ESC). In ESC, crack propagation through plastics subjected to stress is accelerated by weak interaction of the plastic and the chemical. HF is thought to be the worst chemical environment for failure of fluoropolymer diaphragms.

Saint-Gobain Performance Plastics testing strategy

Saint-Gobain Performance Plastics (SGPPL) has developed a testing program for its products and components. The program calls for separate protocols for particle purity, metallic extractables, and reliability. Purity goals are based on the specifications set by BOCE.

SGPPL measures shedding of particles from passive components by monitoring particle release into flowing ultrapure water. Active components, such as valves and pumps, are also tested for particle release into ultrapure water during operation, e.g. valve cycling.

Leaching of metallic contaminants from components is measured using the DyconE^{xSM} dynamic extraction procedure [5] to determine the rate of metal extraction over time. Theory predicts, and test results demonstrate, that the rate of metal extraction from components decreases over time. The dynamic extraction tests are performed in HCl because it is one of the most effective acids for extracting metals from fluorinated polymers [4].

The DyconE^{xSM} dynamic extraction procedure has several advantages over procedures in which metal concentrations in an extractant are measured at the end of a static soak period. Unlike conventional methods, dynamic extraction can measure and predict the rate of change in extraction rate. Use of a small chemical volume and multiple sample points makes the method sensitive enough to detect very low levels of extractables. The data can be used to predict a component's contribution to contamination in a process chemical stream [6]. In addition, the method can be used to distinguish between surface and bulk contamination. This provides an understanding of how a component will affect a system at startup and over time.

SGPPL measures the reliability of active components, such as valves and pumps, in both 37% HCl and 49% HF, ensuring that failure by different mechanisms will be detected. The tests are continued until 70% or more of the components have failed. This provides adequate basis for statistical analysis of failure.

Benefits of testing

A testing program benefits manufacturers in several ways. It can be used to measure and verify component performance, thereby increasing customer confidence. In addition, it allows component manufacturers to make informed decisions about process changes. For example, new materials or cleaning processes can be evaluated to ensure that they maintain or improve component quality.

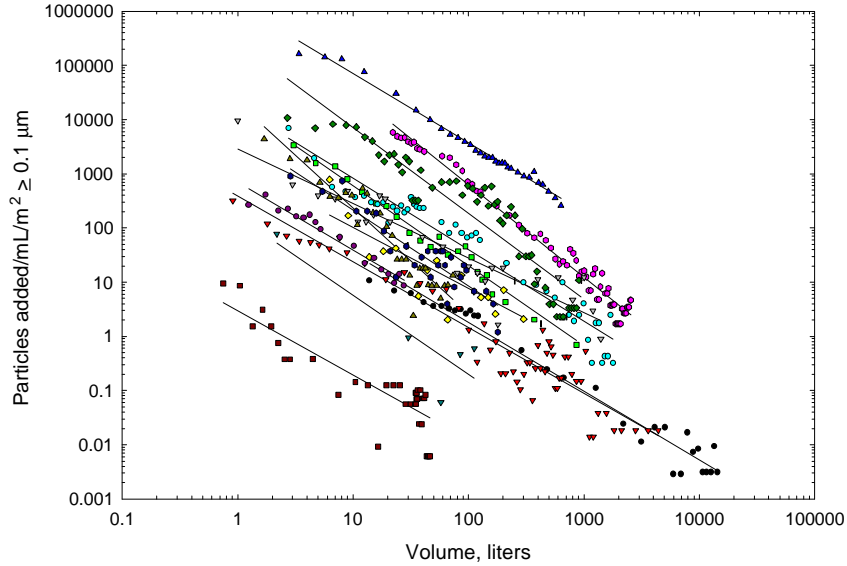
Experimental procedures – Particles

Particle cleanliness is tested by measuring particles shed into ultrapure water (UPW, >18M Ω -cm resistivity, <5 ppb TOC, <0.1 particles/mL \geq 0.10 μ m) by a component. Inactive components, such as tubing and tanks, are measured for passive shedding under steady-flow conditions. For active components, such as valves, particle shedding is also measured while the component is operating.

The steady-flow test for particle shedding has been used in many tests with multiple types of components from different manufacturers [7]. These components had a wide range of initial particle cleanliness levels. The face velocities used in the tests created both laminar and turbulent flow conditions. Reynolds numbers ranged from 100 to 30,000. Shedding was independent of velocity and linear on a log-log plot when plotted as concentration of particles added versus flush volume as shown in Figure 1.

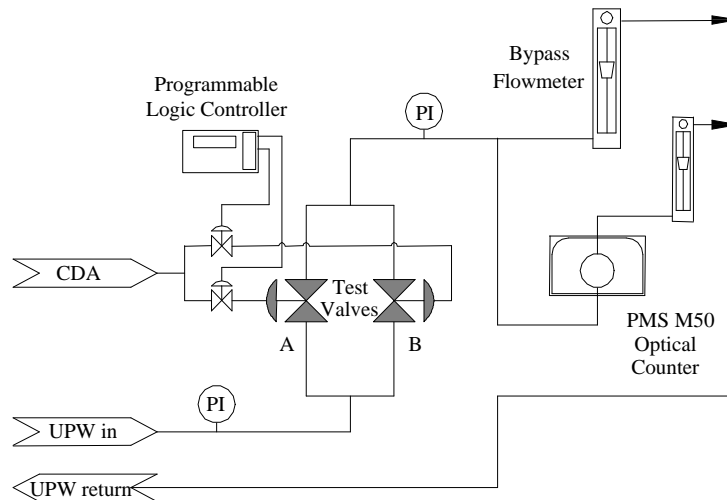
DyconE^{xSM} is a procedure patented by BOC Edwards (U.S. Patent No. 5,641,895). BOC Edwards has granted CT Associates, Inc. a license for commercial use of this procedure.

Figure 1. Particle addition by a variety of fluid-handling components under steady-flow conditions



A typical system used to measure particle shedding is shown in Figure 2. UPW enters the system and flows through the component(s) to be tested at a flow rate calculated to yield a Reynolds number of approximately 1,000. The pressure of the UPW is regulated by a bypass flowmeter and measured both upstream and downstream of the component(s). The UPW flows through an optical particle counter (HSLIS M50 from Particle Measuring Systems in this example) which measures concentrations of particles $\geq 0.05 \mu\text{m}$ in a 100 mL/min flow stream. In Figure 2, the test components are valves. The valves can be tested for passive shedding or actuated with compressed dry air (CDA) by a programmable logic controller to determine particle shedding during actuation.

Figure 2. Test system used to measure active and passive particle shedding from components



Prior to each test, the background particle concentrations of the system are measured. A spool piece is used in place of the component(s). Once the system has stabilized and background particle concentrations are established, the spool piece is replaced with the component(s) to be tested.

Passive testing

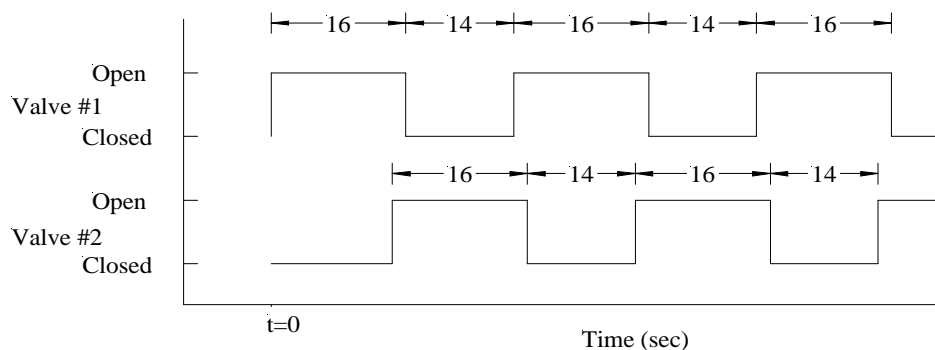
During steady-flow tests for passive particle shedding, a single component is installed in the system and flushed until background particle concentrations are achieved or until flush volume reaches 1,000 L. Concentrations from testing two to four parts of each type are averaged to determine part cleanliness.

Particle shedding tests of active components

Active components often shed particles as they operate. For example, when valves open or close a burst of particles may be released into the fluid stream. Particle shedding from active components is measured first using a passive, steady-flow test then during operation of the component.

To measure active shedding, valves are installed in parallel and cycled two times per minute using the pattern shown in Figure 3. Operation of valves using this pattern minimizes system hydraulic shocks and ensures a constant pressure and flow rate at the particle counter. The valves are cycled through the open/close cycle a minimum of 2000 times.

Figure 3. Actuation pattern used during testing of valves for particle shedding during operation



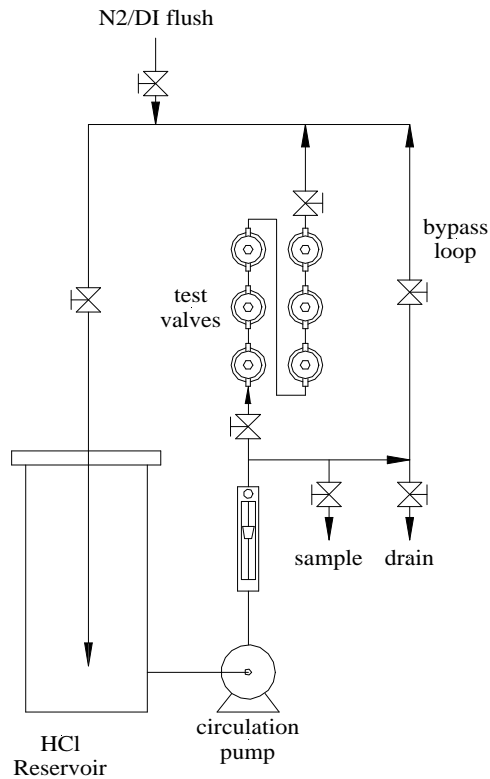
Experimental procedures – Metallic extractables

In any test for metallic contamination in components, it is important to distinguish between surface and bulk contamination. Failure to do so can lead to incorrect conclusions about the cleanliness of a component or the efficacy of a cleaning process. Bulk contaminants must be quantitated because they can continue to leach from components during microcircuit production.

The DyconE^{x SM} dynamic extraction technique is used to determine the type and rate of trace metal extraction from components. Both surface contamination and bulk extraction are determined. Surface contamination has been defined as the mass of contamination removed within 40 minutes of exposure of the component to the extracting chemical. Subsequent extraction is considered extraction from the bulk of the component material.

A DyconE^{x SM} dynamic extraction test system is shown in Figure 4. All of the wetted system components are made of fluoropolymers. The test system has been preconditioned in concentrated (35 to 37%) hydrochloric acid to eliminate measurable metal extraction. The system is located in a class 100 cleanroom. Test components are plumbed into the test apparatus. The number of components used depends on the component internal surface area. Enough components are included to ensure a minimum of 300 cm² of wetted surface area.

Figure 4. Test system used for dynamic extraction procedure to measure metal extraction from valves



Trace-metal quality, concentrated HCl is used as the extractant during this test. To maximize the sensitivity of the test, the volume of hydrochloric acid is minimized. The initial volume includes enough chemical to fill the system plumbing and test components plus an additional 750 mL for chemical samples. Approximately 1 L of HCl is usually required.

Flow of HCl through the test component(s) is maintained at 300 mL/min throughout most tests. Higher flow rates are used for large components. The system is charged with chemical and a

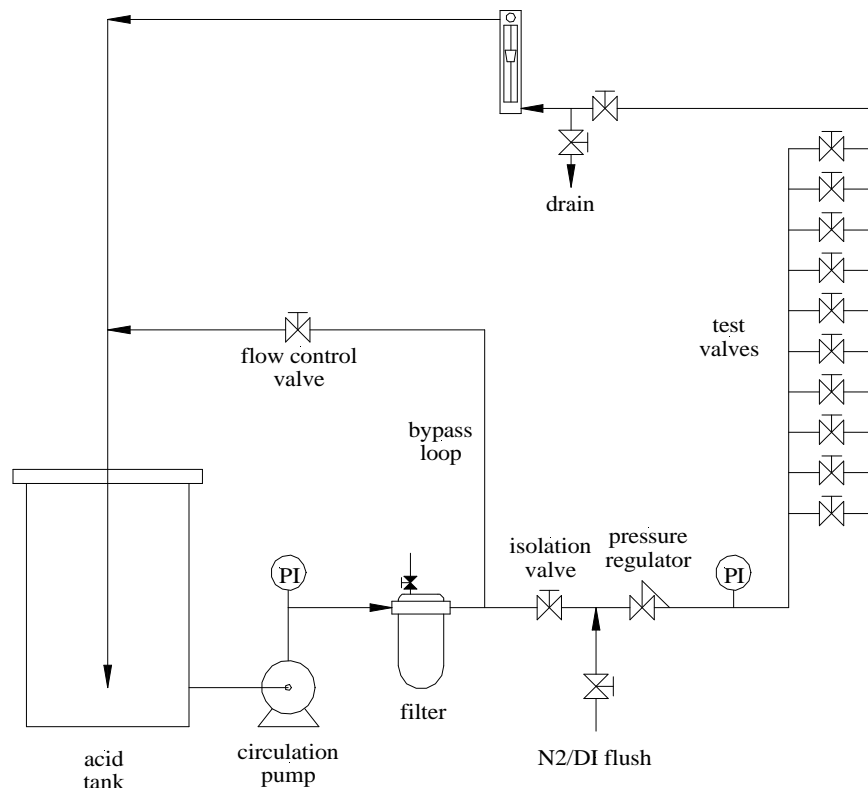
background sample is taken from a sample port located in the circulation loop just prior to initiating circulation of the chemical through the component to be tested. Samples are taken at approximately evenly spaced time intervals on a log scale. The chemical samples are analyzed as a group for 20 trace metals using inductively coupled plasma-mass spectroscopy (ICP-MS) and graphite furnace atomic absorption spectroscopy (GFAAS). The results of the analyses are converted to cumulative mass extracted and normalized for the wetted surface area of each component.

Experimental procedures – Reliability

The procedure for testing the reliability of components must encompass the most likely failure mechanisms. For valves, testing in both HCl and HF is required. To have sufficient data for statistical analysis of failure, at least ten valves must be tested. The valves are run through open/closed cycles until at least 70% of the valves have failed. Data are analyzed for median cycles to failure and the number of cycles at which 5% of the valves have failed.

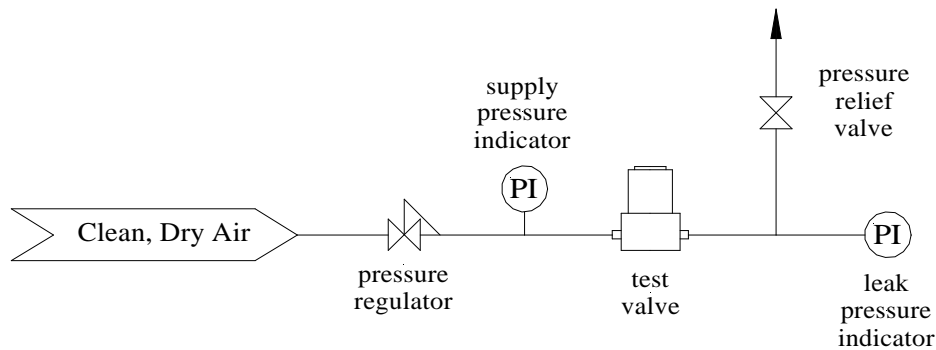
Ten valves are assembled in a test manifold allowing parallel flow of chemical through all valves (Figure 5). The valves are cycled approximately six times/minute with an actuator pressure equal to the lower of 70 psi or the maximum valve rating. The chemical is supplied to the valves using a double diaphragm pump drawing from a chemical reservoir. The chemical supplied to the valves is maintained at a pressure of 65 ± 5 psi. Cleanroom grade (low particle) chemical is filtered through a $0.45 \mu\text{m}$ filter prior to entering the valve manifold. Chemical is replenished every 200,000 cycles to ensure that full chemical strength is maintained.

Figure 5. System for reliability testing



Valves that leak or show other visible signs of failure are immediately removed from the system. Valves that show no visible signs of failure are removed from the system every 200,000 cycles to test for port-to-port integrity and cracking pressure. Cracking pressure is determined by applying air pressure to the closed valve and measuring the pressure at which the valve opens (Figure 6). The test is conducted on both the inlet and outlet of the valve. Maximum cracking pressure measured is 125 psi. If the cracking pressure is greater than 120% of the rated pressure, the valves are returned to the test manifold. Valves with cracking pressures of $\leq 120\%$ of the rated pressure of the valve are tested for port-to-port integrity. This test measures the rise in pressure downstream of the valve when the rated pressure is applied to the closed valve. Valves fail if the pressure rise corresponds to a leak rate in water of ≥ 0.0001 mL/min or ≥ 0.14 mL/day.

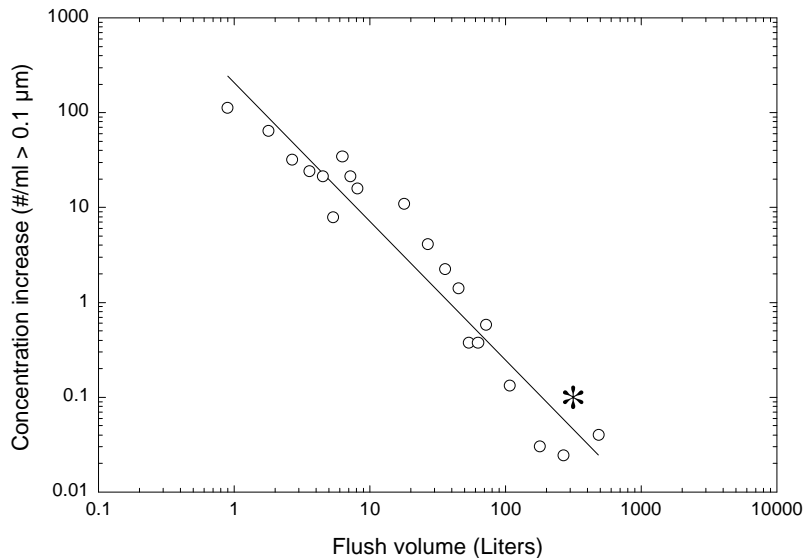
Figure 6. Test stand for measuring cracking pressure and port-to-port leakage



Examples of data analysis – Steady-flow test of particle shedding

Particle shedding from SGPPL CDV valves during steady flow is shown in Figure 7. Particle shedding from each component was calculated by subtracting the system background from each sample's concentration. Particle addition decreased linearly with flush volume on a log-log scale, as expected.

Figure 7. Particle shedding from CDV valves under steady-flow conditions

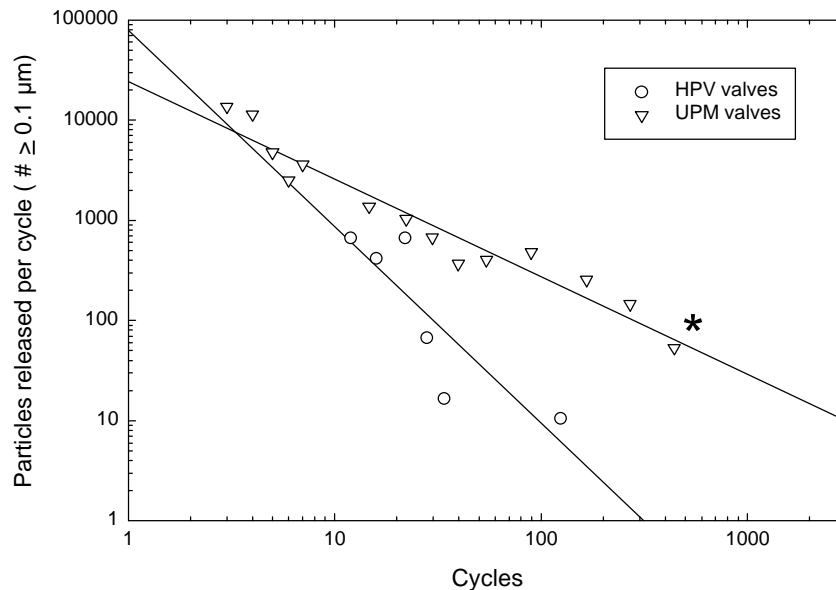


The asterisk in Figure 7 shows the SGPPL purity goal for particle release from active components such as valves (< 0.1 particles/mL $\geq 0.1 \mu\text{m}$ added within 300 L of flushing). The regression line for the data must fall below the asterisk for the goal to be achieved. Figure 7 shows that the CDV valves met the goal.

Data analysis – Particle shedding during valve cycling

The results of cycling tests of SGPPL's HPV valves and UPM valves are shown in Figure 8. The graph shows the number of particles released per valve cycle versus total valve cycles. To meet the SGPPL purity goal, the number of particles ($\geq 0.1 \mu\text{m}$) released per cycle must be less than 100 within the first 500 cycles. This point is represented in Figure 8 by an asterisk. Both types of valves surpassed the goal: particle release from the HPV and UPM valves fell below 100 particles/cycle in just 30 and 280 cycles, respectively.

Figure 8. Particles released from UPM and HPV valves during cycling



Data analysis - Metallic extractables

Concentrations of calcium, iron, and the total of 20 metals extracted by concentrated HCl from HPV valves cleaned using a proprietary procedure are shown in Figure 9. Figure 9A shows the concentrations during the first three hours of extraction. Surface contamination is defined here as the contamination removed in the first 40 minutes of contact with chemical. The rise in concentrations in subsequent samples is due to extraction from the bulk of the component. The concentration increases due to bulk contamination are calculated by subtracting surface metal concentrations from subsequent samples. Figure 9B shows bulk extraction over the entire 290-hour extraction period.

Figure 9. Extraction of selected metals from cleaned HPV valves

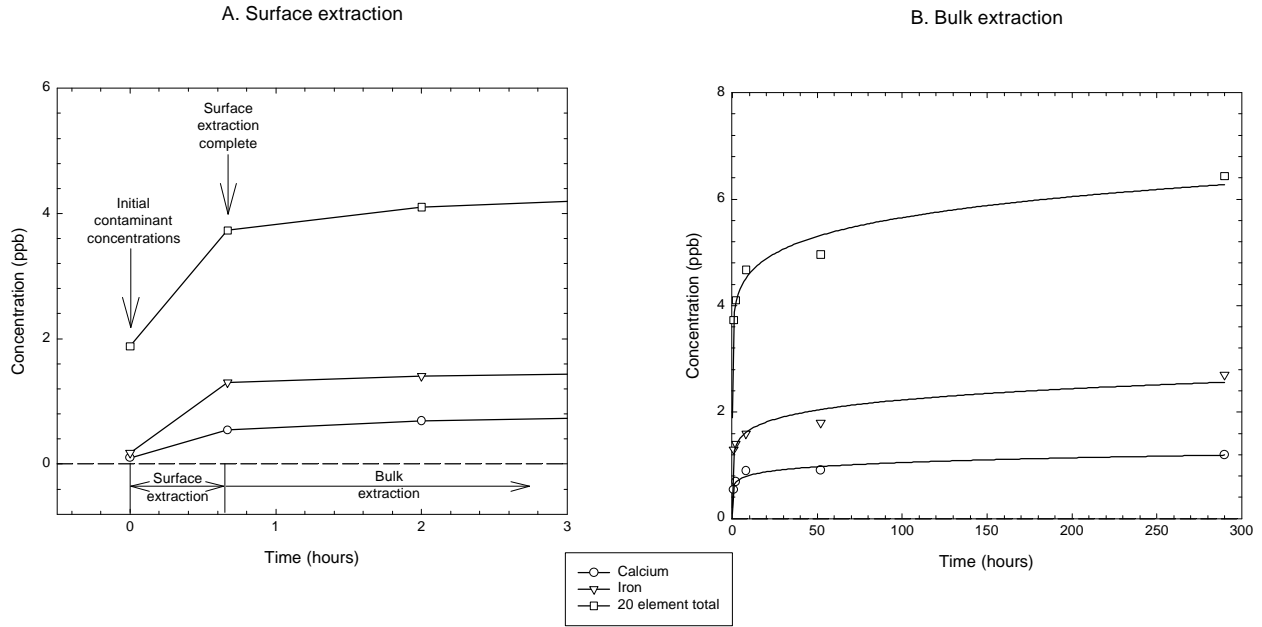
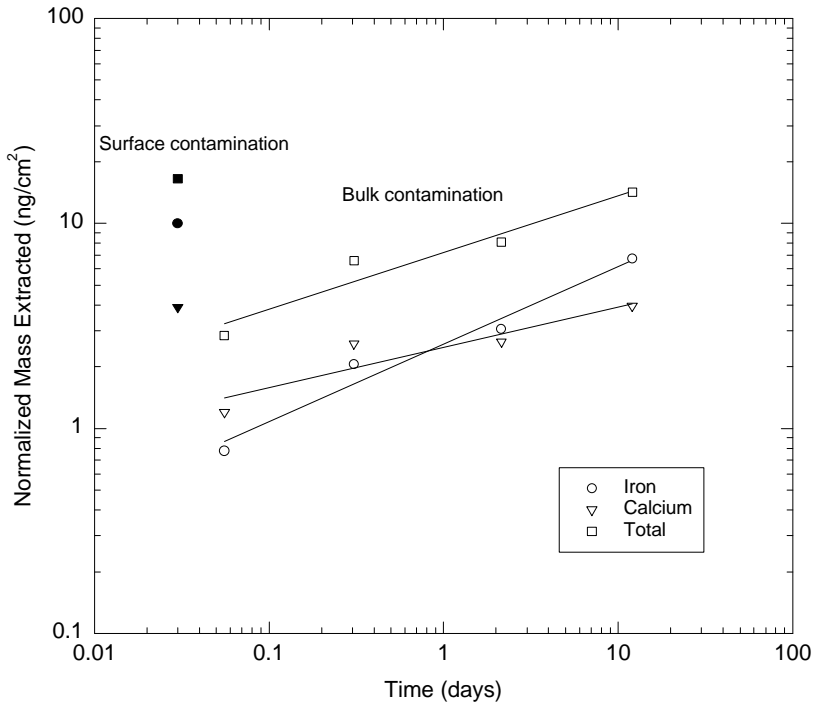


Figure 10 shows the same data expressed as mass of metal extracted per unit area of wetted surface. The filled symbols represent surface contamination. The data show that bulk extraction of metals is linear with time on a log-log scale as predicted by theory [5]. Regression lines have been added to the plot.

Figure 10. Masses of metals extracted from cleaned HPV valves



The mass of metal extracted at any time can be calculated using equation (1):

$$m = k \times t^n \tag{1}$$

where:

- t = time (days)
- m = normalized cumulative mass extracted (ng/cm²) at time t
- k = proportionality constant
- n = exponent

The values for constants k and n can be used to calculate the total mass extracted from components at different times using equation (1). In addition, the rate of extraction can be determined using the derivative of equation (1) with respect to time:

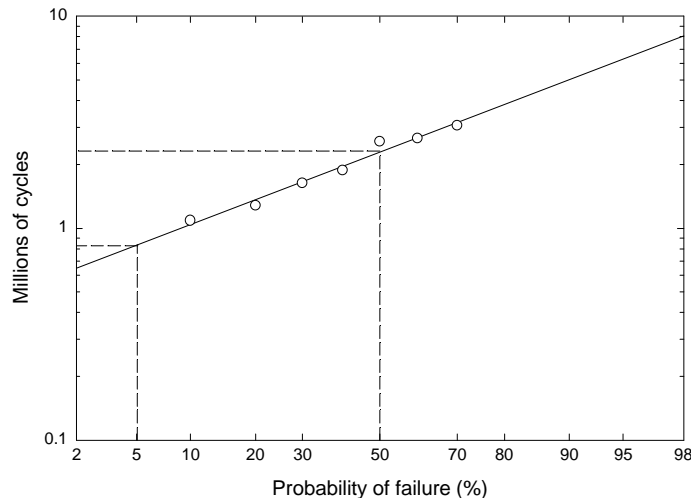
$$\text{Rate of extraction} = dm/dt = n \times k \times t^{n-1} \tag{2}$$

Based on equation (2) the normalized mass extraction rate at 7 days calculated from the HPV valve data was 0.49 ng/cm²-day. The total surface contamination for 20 elements was 16.5 ng/cm². These valves met the SGPPL purity goals for metal extraction from active components for both surface (≤ 20 ng/cm²) and bulk (≤ 0.5 ng/cm²-day after 7 days) contamination.

Data analysis - Reliability

The results of a reliability test of CDV valves in 49% HF are shown in Figure 11. The data are expressed as the probability that a valve will fail as a function of millions of valve cycles. The data from this and other tests have indicated that failures were lognormally distributed and the following analysis is based on that assumption. (For those unfamiliar with lognormal distributions, a good explanation can be found in reference 8.) The x-axis in Figure 11 is a probability scale while the y-axis is a log scale. The solid line represents a fit of the data to a lognormal distribution. The dashed lines indicate the number of cycles completed when the valves reached 5% and 50% failure. There is a 5% probability of a CDV valve failing in HF by 830,000 cycles and a 50% probability of failure by 2.3 million cycles.

Figure 11. CDV valve reliability in 49% HF



Results

The results of particle cleanliness tests are summarized in Table 1. Both steady-flow and cycling test results are included. The SGPPL purity goals are included for reference. The ½-inch tubing, the only passive component included in the table, has different specifications than the active components (note 1). Comparison of the data with the purity goals shows that the tubing and UPM valves met both goals. The CDV, HPV, and J valves each met one of the two goals.

Table 1. Summary of particle cleanliness testing

Component	Steady-flow tests	Cycling tests
	(Volume to <0.1 particles/mL ≥ 0.1 μm added, liters)	(Cycles to <100 particles ≥ 0.1 μm released per cycle)
½-inch tubing	60 ⁽¹⁾	NA
UPM valves	250	280
CDV valves	190	> 2000
HPV valves	940	< 100
J valves	850	310
SGPPL purity goal	≤ 300	≤ 500

(1) The goal for passive components (tubing, piping, tanks, etc.) is < 2/mL/m² added within 1000 L.

Table 2 summarizes the results of the metal extraction tests. The SEMI specification refers to total metal extraction under other, presumably less stringent, conditions and is included here for information only. All of the components tested met the purity goals except the J valves and HPV valves.

Table 2. Summary of metal extraction data in concentrated HCl

Component	Mass extracted (ng/cm ²)			Extraction rate at 7 days (ng/cm ² /day)
	Surface	Bulk	Total	
Standard	180	36	216	0.61
½-inch tubing	0.29	0.48	0.77	0.02
¾-inch unions	7.1	2.0	9.1	0.04
UPM valves	3.6	3.3	6.9	0.11
CDV valves	14	7.8	22	0.28
HPV valves	180	36	216	0.61
J valves	19	26	45	0.87
Check valves	12	9.5	22	0.35
SGPPL purity goal	≤ 20			≤ 0.50
SEMI specification			≤ 12 ⁽¹⁾	

(1) Specification for parts in UPW at 85° ± 5°C.

The HPV valve test data shown above indicate that the valves failed to meet both the metal extraction and the particle shedding purity goals. A better process for cleaning these components is needed. Recent investigation has shown that a proprietary patent-pending cleaning process works very well for reducing contamination. HPV valves cleaned with this process have been tested for both particle shedding and metal extraction. Tables 3 and 4 show that the valves cleaned with the new process met all purity goals. SGPPL is in the process of implementing this cleaning process.

Table 3. The effectiveness of a proprietary cleaning process in reducing particle shedding from HPV valves

HPV valve clean	Steady-flow tests (Volume to < 0.1 particles/mL ≥ 0.1 μm added, liters)	Cycling tests (Cycles to < 100 particles ≥ 0.1 μm released per cycle)
Standard	940	< 100
Proprietary new	24	< 100
SGPPL purity goal	≤ 300	≤ 500

Table 4. The effectiveness of a proprietary cleaning process in reducing extractable metals from HPV valves

HPV valve clean	Mass extracted (ng/cm²)			Extraction rate at 7 days (ng/cm²/day)
	Surface	Bulk	Total	
Standard	180	36	216	0.61
Proprietary new	16	14	30	0.49
SGPPL purity goal	≤ 20			≤ 0.50
SEMI specification			≤ 12 ⁽¹⁾	

(1) Specification for parts in UPW at 85° ± 5°C.

Reliability test results are summarized in Table 5. The J and CDV valves had median cycles to failure of 1.4 and approximately 2.5 million cycles. Tests with the HPV valves are in progress with no failures after 7 million cycles. UPM valves showed no failure after 1 million cycles. Additional testing is planned to determine failure statistics.

Table 5. Statistics of failure and failure mode

Valve	Test fluid	Statistics of failure		Main failure mode
		Median (million of cycles)	Geometric standard deviation	
UPM	37% HCl	> 1.0 ⁽¹⁾		
J	37% HCl	1.40	1.45	Spring
HPV	37% HCl	> 7.0 ⁽²⁾		
CDV	37% HCl	2.90	1.14	Spring
CDV	49% HF	2.28	1.85	Diaphragm

- (1) Both ¼- and ½-inch valves tested to 1.0 million cycles with no failures.
(2) Valves cycled 7.0 million times with no failures.

The reliability data are presented in Table 6 as cycles to 5% and 50% probability of failure. This method of expressing the data is useful in deciding how frequently valves should be replaced. All valves tested had 5% failure rate at more that 0.7 million cycles, with the HPV valve failure rate at > 6 million cycles.

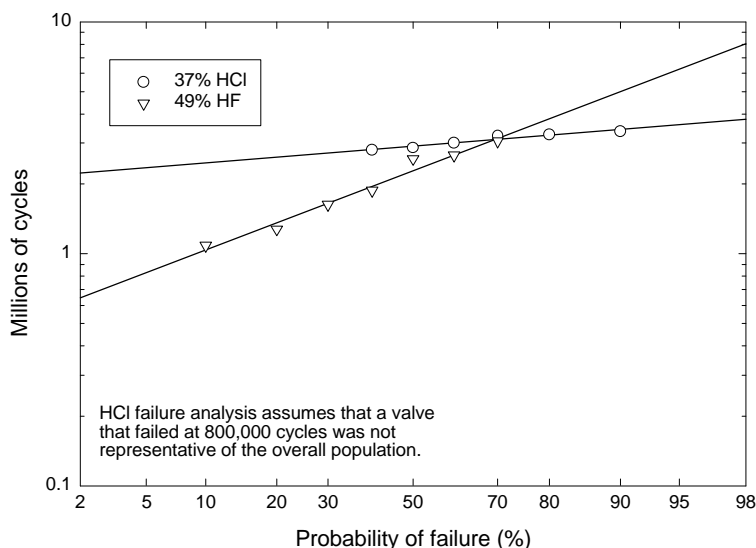
Table 6. Valve cycles to probability of failure

Valve type	Test fluid	Failure rate (millions of cycles to failure)	
		5% Failure	50% Failure
UPM ⁽¹⁾	37% HCl	> 0.86	> 1.7
J	37% HCl	0.76	1.4
HPV ⁽¹⁾	37% HCl	> 6	> 11
CDV ⁽²⁾	37% HCl	2.3	2.9
CDV	49% HF	0.82	2.3

- (1) Failure rate was estimated because no failures were observed during testing. Estimates were made assuming that failures are lognormally distributed with a geometric standard deviation of 1.5, and that 1 of 10 valves failed 1 cycle after the last test point. The value of 1.5 assumed for the geometric standard deviation was based on historical data.
(2) Failure rate was estimated assuming that a failure at 800,000 cycles was not representative of the general valve population.

The median cycles to failure for the CDV valves in HF and HCl were similar. However, the failure modes were different and failure times were more variable in HF, as shown in Table 6 and Figure 12.

Figure 12. Failure rates of CDV valves in HF and HCl



Summary

The component testing program has shown that most Saint-Gobain Performance Plastics (SGPPL) components meet the stringent semiconductor industry needs for purity. The most notable exception is the HPV valve that fails to meet the goals for steady-state particle shedding and metal extraction. However, a new, proprietary cleaning process has proved to be effective for reducing both particle shedding and metal extraction from these valves. SGPPL and CT Associates are designing a production process to implement this clean for reducing contamination in all critical components made by SGPPL, including HPV valves.

Reliability testing has shown that most SGPPL valves have mean times to failure in excess of 1.5 million cycles when cycled in harsh acids. Failure appears to occur earlier in 49% HF than in 37% HCl. The main failure modes in HF and HCl are diaphragm failure and spring failure, respectively.

The component testing program will be continued to ensure that SGPPL products meet industry needs for purity and reliability. The program will be expanded to include other components such as pumps. Additional tests will be run to collect data on reliability in HF. The new, proprietary cleaning process will be implemented as a part of the manufacturing process to further improve purity.

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Biographies

Don Grant is president of CT Associates, Inc., which performs contract research and development in contamination control, particle measurement and control, filtration and chemical engineering. He has more than 25 years of experience in analysis and purification of fluids and is the author or co-author of more than 100 technical papers and presentations. He has an M.S. in mechanical engineering from the Particle Technology Laboratory at the University of Minnesota and a B.S. in chemical engineering from Case Western Reserve University. He is a recipient of the Maurice Simpson Award from the Institute of Environmental Sciences.

Dennis Chilcote is a consulting engineer with CT Associates, Inc. His particular areas of expertise include biotechnology, water treatment, and environmental engineering. His broad experience in process design has been applied to the leaching of metals in aqueous solutions, the development of clinical instrumentation, and the design and fabrication of a variety of water treatment processes. He received his PhD in chemical engineering from the California Institute of Technology, with emphasis on bioengineering. He also holds a BS in chemical engineering from the University of Minnesota.

Wayne Kelly joined CT Associates, Inc. in 1994. His areas of expertise are liquid filtration and microcontamination. He received a B.S. degree from the University of Kansas and an M.S. degree from the University of Minnesota, both in mechanical engineering. Prior to joining CT Associates, he worked at TSI Incorporated in the Contamination Monitoring Instruments Group.

Mark R. Litchy joined CT Associates, Inc. as a research engineer in 1996. He has several years of experience in particle measurement and control in high-purity liquid chemicals and gases, as well as surface contamination and cleaning. He has an M.S. degree in mechanical engineering

from the Particle Technology Laboratory at the University of Minnesota and a B.A. degree in physics from St. John's University.

Allen Rodemeyer has been with Saint-Gobain PPL since 1993 and presently supervises the Research and Development Laboratory for the Engineered Components Group. He has over 18 years of experience in a research and development environment dealing in destructive, non-destructive, environmental, and reliability testing. He currently holds an A.S. in electronic technologies from Riverside Community College and is presently working to complete a B.S. in mechanical engineering at Cal State Fullerton.

Dave Henderson is a Market Engineer for Saint-Gobain Performance Plastics. He has a B.S. in Electrical Engineering and 10 years experience in fluid-handling product design and semiconductor process applications. He is an active member of SEMI standards committees and is an author of three Patents, two of which have issued.

Kenji Kingsford is Director of Technology for Saint-Gobain Performance Plastics. He has a B.S. in Mechanical Engineering and 17 years experience in fluid-handling product design for the semiconductor industry. He is an inventor on 17 patents for semiconductor-based products and an active member on SEMI standards committees.