

MICROELECTRONICS

LESSONS LEARNED: THE INSTALLATION OF A 300 TO 600 GPM SEMICONDUCTOR HIGH-PURITY WATER SYSTEM

The life of a high-purity water treatment project may be compared to rolling a boulder down a dome-shaped hill (1). The project gets rolling with a fairly small nudge. Once it is rolling, however, it takes a great deal of effort (time and money) to change the direction or go back up the hill. The project to design, build, install, and commission the "E" high-purity water system at VLSI Technology's San Antonio, Texas, manufacturing site followed this model. Now that we are at the bottom of the hill with a functional system, we will take a look back to see the major decisions and players that made the new system successful.

Every custom water system carries a "flavor" from the owner. VLSI Technology Inc. makes custom and semi-custom integrated circuits (ICs) primarily for the digital communications and graphics industries. VLSI currently has one wafer fabrication plant for production quantities of ICs. This plant in San Antonio has approximately 60,000 square feet of Class 1/Class 100 cleanroom space making a variety of products with minimum line sizes of 0.8 micron (μm) to 0.2 μm on 150-millimeter (mm) (6 inch) wafers. The plant is currently converting to 200-mm (8 inch) wafers. VLSI had 1998 revenue from continuing operations of \$548 million and employs about 2,200 people worldwide of which 600 to 700 work in San Antonio.

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The Start of the Project.

In the summer of 1997, VLSI initiated a project to expand the manufacturing cleanroom by roughly 15,000 square feet. This new space holds chemical mechanical polishing units ([CMP], a process required for line widths of 0.35 μm and smaller) and other fab equipment.

The "E" high-purity water system was built to supply water to the fab to support the extra demand from the CMP process and the conversion to 200-mm wafers. VLSI-San Antonio had four existing water systems operating in parallel with a combined capacity of 600 gallons per minute (gpm). We identified the need for a high-purity water system supplying 300 gpm, but recognized that previous estimating efforts had fallen short by 10% to 25% of eventual demand. We also saw that the water quality from the existing systems was adequate for current technologies, but was starting to cause problems for the manufacturing organization — usually when the systems were not working in "normal" mode.

System Overview

The existing water systems (Trains A through D). Industrial Design Corp. designed the existing systems (A through D). The "A" system was a turnkey project by Aqua-Media built in 1987. The other systems were manufactured by Ionics Pure Solutions (Tempe, Ariz.) in 1991, 1995, and 1996. Dynamic Systems purchased and installed these systems as mechanical contractors. The "A" though "D" systems all had very similar schematics with these characteristics: multimedia and activated carbon beds for pretreatment; polypropylene microfilters; antiscalant injection; single-pass reverse osmosis (RO); two-stage tower vacuum degasifiers; *in-situ* regeneration mixed beds; low pressure 185-nanometer (nm) and 254-nm ultraviolet (UV) lamps; polypropylene UF prefilters; and polysulfone ultrafilters as the final filters.

VLSI also had developed a paradigm in terms of control, redundancy, parallel operation, and system sterilization. This

paradigm included the following characteristics:

1. High-purity water systems operate in parallel, except for unusual maintenance or emergency conditions.
2. The systems are designed for a maximum flowrate, and do not have the ability to be expanded.
3. All unit operations in the fab must have redundant equipment on separate utility systems. For example, the sulfuric strip process needs to have one wet station served by "B" and one served by "D."
4. Pumps, primary mixed beds, and other high maintenance operations have redundant equipment installed side by side.
5. Polishing mixed beds and vacuum degasifiers are not redundant.
6. Various resin vendors can be used in different systems depending on who offers the best quality, service, and price at the time of purchase.
7. Sterilization is by ozone on an annual basis unless bacteria counts indicate a problem.
8. VLSI relies on off-site laboratories for water analysis beyond the on-line instruments.
9. All systems are to have local control by an independent programmable logic controller (PLC) reporting up to a facilities building management system. Programming is considered to be of very high importance and is only entrusted to known good programmers.

Even though almost 10 years had passed between the commissioning of "A" and "D", the changes to the systems were very slight. Taller mixed beds, better instrumentation, and hollow fiber ultrafilters were used in the newer systems, but not in the older.

In keeping with its operational philosophies, VLSI employs a highly experienced, lean operational staff. The deionization (DI) water facility is typically being operated by two dedicated operators, with support from general facilities technicians when the DI operators are

TABLE A
Design criteria for the "E" High-Purity Water Train

	<i>VSLI Requirements</i>	<i>Actual Performance</i>	<i>Remarks</i>
Product water flow	300 gpm	300 gpm	expandable to 600 gpm
Product water quality, primary mixed bed	17.5 megohm-cm	>17.5 megohm-cm	(A)
Product water quality, polishing mixed bed	18.2 megohm-cm	18.2 megohm-cm	(A)
Dissolved oxygen, degasifier effluent, ppb	<2	<1	(B)
Silica, primary, ppb	<0.2	<0.2	reactive silica (C)
Silica, polishing, ppb	<0.2	0.1	reactive silica (F)
TOC, final product	<1.5	<1	(D)
Particles, final product, $\geq 0.05 \mu\text{m}$	<1 per 2 minute	<1 per 2 minute	(E)
Sodium, ppt	<20	<20	ion chromatography(F)
Boron, ppt	<500	100-200	ICP/MS (F)
Bacteria, cfu/100 mL	<1	<1	(F)
Regeneration time allowed	8 hours maximum (6 consecutive regenerations)	meets spec.	
Number of key operators allowed	One (1)		

Notes:

- (A) Resistivity using CR 200, Thornton Associates, Waltham, Mass.
- (B) Dissolved oxygen measured by unit from Orbisphere Laboratories, Emerson, N.J..
- (C) Silica measurement by Series 6000, Hach Co., Loveland, Colo.
- (D) TOC measurement by Model A-1000, Anatel Inc., Boulder, Colo.
- (E) Particle measurement by HSLIS-M100, Particle Measurement Systems, Boulder, Colo.
- (F) Analytical services supplied by Balazs Analytical Laboratory, Sunnyvale, Calif.

not available. So, there is an extreme focus on keeping man-hours for routine operations to a minimum.

The new water system (Train E) currently uses surplus, pretreated water from RO Trains A through D. As already noted, the existing pretreatment system consists of multimedia filters, carbon filters, scale inhibitor feed systems, and RO systems.

All major components for the "E" system were designed and manufactured by U.S. Filter (also referred to as the new equipment supplier). This system uses many state-of-the-art technologies: membrane degasifier; medium pressure, primary UV sterilizers; primary mixed-bed units with Halar® lining (external regeneration); medium-pressure polishing UV sterilizers; polishing mixed-bed units with Halar® lining (external regeneration); ultrafiltration (UF) booster pumps, electropolished stainless steel construction; polishing 0.2- μm (absolute) cartridge filters with polyvinylidene fluoride (PVDF) lined housing; polishing capillary UF system; polyvinylidene fluoride high-purity water distribution loop with a medium pressure UV sterilizer on the return pipe; regeneration supply DI water storage tank with medium pres-

sure UV sterilizers on the effluent; hydrochloric acid (HCl) and sodium hydroxide (NaOH) feed systems with chemical day tanks; and clear polyvinyl chloride (PVC) resin transport piping.

Additionally, there is an external regeneration system that includes a separation column, cation regeneration column, and anion regeneration column. This system has been designed to regenerate either 75 cubic feet (ft³) of high-purity water grade mixed-bed resin (Train E) or 50 ft³ of high-purity water grade mixed-bed resin (Trains A through D).

Performance Requirement of New System

The new equipment supplier was required guarantee not only the routine performance (refer to Table A) but also the maximum allowable time (8 hours) for the regeneration of either 50 ft³, or 75 ft³ of mixed bed resins. Finally, the equipment supplier was required to demonstrate that one operator could operate the system. These performance criteria have been met.

Technologies Evaluated

During the early stages of project development, the VLSI high-purity water team

decided to evaluate the following process technologies.

- Double-pass RO versus single pass;
- Electrodeionization (EDI) versus primary mixed beds;
- Resin regeneration: *in-situ* regeneration versus external regeneration;
- Dissolved oxygen removal: two-stage vacuum degasifier versus membrane degasifier;
- Medium-pressure UV sterilizers versus traditional UV sterilizers;
- Mixed-bed vessel lining materials: rubber lining versus Halar® lining;
- DI water storage tank design: PVDF lined versus fiber-reinforced plastic; and
- UF booster pumps: Non-metallic pumps versus electropolished pumps.

Criteria. The high-purity water team agreed to evaluate these technologies on predetermined criteria, such as cost impact, impact on final product water quality, space requirements, schedules, and reliability of operation.

In evaluating new technologies for the "E" system, we developed several crite-

ria for acceptance. They were as follows:

1. Do not change the job of any unit process in the system. We would improve how that function is carried out, but not drastically alter the water chemistry at any given point. This was done to maintain crossover capability since all five systems would be tied together at key points. This also decreased the probability of poor product water due to interaction between unit operations.
2. The operator's time was given a very high priority in system operations.
3. Whenever possible, metal was not to come in contact with the water.
4. Any new technology needed to be demonstrated in at least one other semiconductor facility with similar design rules for integrated circuit manufacturing.

Technologies Selected

In the final analyses, the high-purity water team recommended to proceed with an external regeneration system, a membrane degasifier, Halar[®]-lined mixed-bed columns, and medium-pressure UV sterilizes (185 nm), FRP DI water storage tank, and electropolished UF booster pumps.

Double pass RO and EDI. The use of double pass RO and EDI was rejected because it violated the first criterion set forth in the above section. It did meet the others, but since this system was for an expansion of a fully qualified factory, we decided against it. Other factors included:

With VLSI's operational paradigms, this technology has a potential problem with boron levels being higher than specified.

Chemical tanks and pH neutralization systems are already in place, so there was no cost savings for eliminating them.

To serve *in lieu* of the primary mixed beds, the existing RO process would have to become a double-pass system. This would add cost to the existing plant to modify it.

The project oversight team decided to delay the RO makeup train until there is a need for more RO capacity.

In-situ regeneration versus external regeneration. External regeneration

was selected due to price and quality issues. It enables us to do the following: keep the regeneration chemicals away from the main process stream; eliminate the metal internals on the mixed-bed exchange vessels; simplify the piping schemes at the mixed beds; control the regeneration process much more tightly leading to better quality (i.e., lower sodium leakage); remove resin fines; and control the reconditioning of resin. The system will also enable on-site regeneration of polishers for a future new manufacturing building.

The system was designed to regenerate complete batches of resin with only trivial cross contamination from one batch to the next. That is, there was no "heel" of resin left in the separator column after resin transfer to the anion and cation vessels.

Two-stage tower vacuum degasifier versus membrane degasifier.

Selection of membrane degasifier *in lieu* of traditional two-stage vacuum degasifier towers was one of the boldest decisions. There were very few installations such as this at the time in the United States, and even the original equipment manufacturers (OEMs) bidding on this job did not offer much help. In the final analysis, the high-purity water team members were quite comfortable with membrane degasifier technology. This application had a lower installed price for the following reasons: lower cost due to a smaller footprint, smaller vacuum pumps, and no need for repressurization after the unit.

This technology also offered these quality advantages:

1. Better modularity (so that we can work on one array with the others still in operation);
2. Better ability to achieve very low dissolved oxygen levels;
3. Simpler controls; and
4. More flexibility to meet future requirements.

Rubber lining versus Halar[®] lining of ion-exchange units.

This was a split decision due to cost versus quality. We used rubber on the regeneration vessels and Halar[®] on the primary and polishing ion-exchange units. The quality issues in favor of Halar[®] are as follows: a smoother and harder surface should last longer with fewer repairs; lower levels of metal and organic leaching; and

no seams to catch resin.

Low-pressure versus medium-pressure UV lamps. The medium-pressure UVs had the following advantages: the potential for more total organic carbon (TOC) reduction due to the larger number of high energy photons given off in the sub-254-nm wavelength region; and reduced ongoing operations expense for the replacement of bulbs.

FRP versus PVDF-lined DI water storage tank. Fiber-reinforced plastic with a vinyl ester resin coating was selected. Initially there were concerns that the FRP material for DI water storage tank material would require unacceptable rinse time to bring down TOC values. However, some unusual procedures, such as cleaning the tank interior with steam, helped with rinse down time. Total organic carbon levels were quite acceptable: less than 2 ppb within 2 weeks and less than 1 ppb within 2 months. This alternate material represented cost savings of more than \$100,000, which offset the higher cost of Halar[®] lining elsewhere in the system.

Non-metallic pumps versus electropolished pumps.

Choosing electropolished stainless steel pump material *in lieu* of non-metallic materials was another big concern, given VLSI's historical problem with transition metals. However, the reliability of non-metallic pumps and lack of site-specific experience were the factors deciding against these designs. The same argument was used in favor of using electropolished stainless steel check valves *in lieu* of non-metallic check valves. However, VLSI's operators are still concerned about possible metal contamination. These items will be inspected regularly.

Selection of Suppliers

The selection of the water treatment OEMs was a major exercise. VLSI wanted to receive bids only from qualified OEMs who had experience, staff, and unique technologies to offer. Thus, a short list was created. This list included Ionics Pure Solution, Glegg Water Conditioning, and U.S. Filter. With the exception of Ionics Pure Solutions, the other suppliers were not familiar with VLSI and vice-versa.

The authors of this article took on the task to personally visit the manufacturing operations of Glegg, and U.S. Filter. Visiting Ionics was not deemed necessary since VLSI knew this company, its

people, and products quite well from past association. Each company was evaluated on the basis of their in-house design and engineering staff experience, computer-aided design (CAD) capabilities (including Pro E drawings capabilities), quality assurance/quality control program, manufacturing process, purchasing capabilities, and materials handling process.

The next effort took VLSI facilities operators to visit similar high-purity water installations by each supplier. This visit provided further insight on how their equipment, with emphasis on the external regeneration system, works. Some design deficiencies were also brought to the high-purity water team's attention. The high-purity water team addressed those issues in the engineering specifications.

It should be noted that the project oversight team made a decision to make the selection of the OEM as early as possible in the project. This was done to include the expertise of the OEM in the design process. Provisions were made in the bid documents to have a negotiated rate for change orders, whether positive or negative. The markup rate for change orders included engineering costs, labor costs, accounting costs, and profit margin for the OEM. This would ensure that the OEM and owner could make changes to the original design and know the costs incurred for that change.

Special Requirements

Reduction in metals contamination.

In 1996, VLSI began experiencing transition metals contamination of the high-purity water systems due to corrosion of stainless steel equipment in contact with the water. After some work, we found a reasonable analytical method that could predict the behavior of wafers exposed to the water. This method has a method detection limit of about 20 parts per trillion (ppt) and is stressed to distinguish between "good" and "bad" water.

We found that any stainless part, especially after the final mixed bed, was a potential source of contamination. The metals levels could only be controlled if the stainless steel surface area in contact with the water was greatly reduced, and the electropolishing process beefed up substantially. Specifically, the chromium-to-iron ratio and the oxide thickness have now been specified, where before they had not. We are also requiring that all of the metal pieces in contact

with the water start out as machined pieces before the electropolishing. In general, PVDF or other high purity plastic is to be preferred over even the best electropolish.

Use of non-PVDF plastics. Because of economic reasons VLSI elected to use PVC for RO product water and regeneration water. Clear PVC was specified for resin transfer piping. For city water service FRP was the material of choice for 8 inch and larger pipe size. Fiber-reinforced plastic has proven to be an excellent material, both from pressure rating and metal elimination points of view.

Start-up Problems

The "E" System started up fairly smoothly for a system of this size. Most of the problems at start-up were really construction issues that had not been worked out adequately. Among these issues were as follows: trenches not finished on time; exterior pipe bridges behind schedule; waste treatment lift station not operational on schedule; and exterior grading not complete on schedule.

The effect of these issues was to compress too many tradesmen into a small area with too little time. This in turn drove trade workers overtime wages up and quality down as rework became a necessity. The crews and management of the installation contractors became exhausted. There were many other potential problems that were caught and rectified, but these caused extra work and money.

Another issue that surfaced during startup was that the instrumentation and controls effort was divided among several companies leading to inconsistency and confusion. Most of these problems were annoyances, but about 3 days delay in the regeneration schedule were due to off-skid valves not operating in the same way as on-skid valves. One issue that surprised the team was the amount of pipe bracing needed to keep the resin transfer pipe locked in place.

However, the system was started and met water quality requirements on schedule. There was a price to pay in overtime to do this. It was on the order of 10% above the ideal mechanical installation budget. This number is actually quite low for a real world project.

There were two issues that surfaced during startup that were not easily traced to any one group. The first was that the

acid waste drain pipe system backed up during certain portions of the regeneration process. The reasons were thought to be inadequate pipe size to allow simultaneous flow of water and nitrogen (used to move ion-exchange resin) in opposite directions. The cure for this was surprisingly simple: a strategically placed valve to isolate the two streams.

The second issue was a kinetic impairment of the ion-exchange resin caused by the acid used during regeneration. This is not completely corrected yet. Apparently the acid day tank was leaching a contaminant that hurt the cation resin's ability to purify water. As the resin rinses down, the ability to purify the water improves, but each regeneration brings the problem back again.

Project Management and Control

The project oversight team.

The facilities group instituted several changes from the previous project management process to improve on the final product. First, a team was formed with representatives from facilities operations, facilities engineering, Spectra Consulting Engineers (the design engineering firm), Dynamic Systems, Purity Water Co. (a firm that provides operations support for high-purity water systems), and Advanced Water Technology Services (who provided engineering support as an owners representative). This was the project oversight team.

Up to this time, VLSI had never used an independent owner's representative throughout a project to build a new water system. Nor had we dedicated this much time and money to reason out and document project programming decisions. We sought to get the ball rolling down the right side of the hill from the very beginning. We wanted to control the process design, project cost, and schedule. We desired to minimize risks and provide a new system that would meet or exceed the demands placed on it for the next 10 years.

Team members were given tasks to investigate new technologies, draft schematics and plans for the new system, pre-qualify potential bidders, communicate decisions to VLSI management, and the wafer fabrication organization, the enduser. The project oversight team as a whole made decisions. These decisions were almost always unanimous — even if it took a great deal of debate to get that unanimity. As time went on the team included representa-

tives from the new equipment vendor, construction foremen, controls specialists, and startup specialists. At the end of the project, team members held a "lessons learned" meeting that was quite productive and forms the core of this presentation.

It may be worth noting here that each member of the team was chosen based on his expertise in a specific area as related to this project. Communication between high-purity water team members, free expression of ideas, and respecting each member's opinions made this team successful and in turn contributed to a successful project. Many issues were dealt with at the earliest stages of the project that otherwise would have cost much more to take care of during the final stages of the project.

A second benefit of the team approach was to have backup personnel available in key positions. During peak stress times, team members could be in several cities at the same time with a common goal. For instance, one person could be at the new equipment vendor's manufacturing facility doing design review and expediting the response to design questions. At the same time, another person was in San Antonio making sure that the building would be ready to accept the system. It also allowed members to take time off to handle health and other personal issues without causing serious harm to the project.

One part of the project oversight team could be improved. The general contractor did not have scheduling resources adequate to meet the needs of the project when it was time to do the massive coordination between trades in a fairly confined space. This created a disconnect between the contracting arm of the project and the operations arm.

This model of operations showed itself to be clearly superior to previous VLSI water system projects and we intend to use the same approach in the future. One modification would be to increase the amount of VLSI facilities engineer, design engineer, and/or owner's representative time in the OEM's shop during the design phase. The design phase stretched out beyond the allocated time and caused much more expensive phases to be compressed.

Summary

In retrospect, this project must be counted as a major success. The system came up on time, on budget, and met quality goals. The project was success-

ful in large part due to the selection of the team members and their dedication to the common goal. When skilled people work together with integrity and dedication, almost all of the energy spent on the project yields a positive result. This project had very little finger pointing and "avoidance of responsibility."

For future projects of this type, we would hope to follow the same basic model of management. It would be desirable to allocate a little more resources up front to experienced engineers who will work on the entire project, especially in transferring design information to the OEM.

All of the new technologies chosen have worked well in operation. In the future, we will probably look to non-chemical regenerations and double-pass RO systems to reduce operating costs. We will also be even more aggressive about removing metal from contact with the water.

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Reference

1. Wilson, M.; VLSI Technology Inc., San Antonio, Texas, personal communication (August 1997).

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