WATER REUSE

THE AWARD WINNING WATER RECLAIM SYSTEM AT PHILIPS SEMICONDUCTORS' SAN ANTONIO WAFER FAB

The semiconductor industry is trying to reduce the environmental footprint of our factories. As has been documented elsewhere (1, 2), today's factories can consume as much water as a large town with a population in the tens of thousands. As the economy of scale drives the size of factories, increasing water consumption will be a huge stumbling block to locating a factory in many communities.

The *International Technology Roadmap for Semiconductors* (ITRS) (2), Sematech, and individual corporations have set targets for water consumption by factories (fabs in the industry jargon). The effort to reduce water consumption must meet economic and quality metrics that are quite stringent. In essence, a water reclaim/recycle system must save money and improve, or at least not hurt, the quality of high-purity water provided to the fab. Also, water reclaim/recycle projects are more economically attractive if they supply a need for new water purification capacity rather than replacing an existing system. So, the project to build the reclaim system will probably take place at the same time as a larger construction project with the constraints on time and resources that come with a major construction job.

A system to significantly reduce water consumption and increase high-purity water capacity at the Philips Semiconductors San Antonio Wafer Fab was designed, installed, and commissioned in 2000-2001. The system won several awards, including the Pioneer Recycling Award from the San Antonio Water System, and the Conservation/Reuse Award from the Texas Section of the American Water Works Association. In addition to these awards, the San Antonio Water System rebated a part of the capital cost of the system in accordance with the "Large Scale Users Industrial Retrofit Program". The potential rebate could reach more than $1 million, based on demonstrated water savings over the next six years.

The Opportunity

In early 2000, the Philips San Antonio Facilities group faced the task of upgrading our plant to support the move to 200-millimeter (mm) wafers and increasing the production levels. We had roughly 11 months to investigate numerous issues and execute needed plant improvements. The data we had available showed adequate high-purity water capacity in the polish loop, but we lacked capacity in the reverse osmosis (RO) make-up trains.

We investigated ways to increase the RO make-up capacity using technology similar to existing equipment, thereby increasing water consumption and disposal costs as compared to water reclaim/recycle. The Philips Environmental Policy states that we will reduce our environmental impact in a manner consistent with fiscal responsibility (3).

Options

Upgrading the existing high-purity water makeup system for more capacity would use the same unit operations as our existing system. It would require installation of a tank/pump system for blending city water with reclaim streams, multi-media filtration, activated carbon filtration, antiscalant dosing, cartridge filtration, and then single-pass RO.

Since 1997, Philips (then VLSI Technology Inc.) had been running a pilot water reclaim system. We accumulated a significant database characterizing the rinse water reclaim (RWR) stream when the fab was running 150-mm wafers. Using this data, we examined options for reclaim of the water to the air pollution abatement systems and recycling the water to the high-purity water system.

The reclaim/recycle option would require the replacement of the pilot system with a full-scale collection and transfer system, and also the addition of a treatment system prior to recycling the water to the high-purity water plant.

Decision Making

Our team weighed the three criteria by which any project is judged: quality, cost, and schedule. Of these three, the quality of the water produced was deemed the most important. Cost and

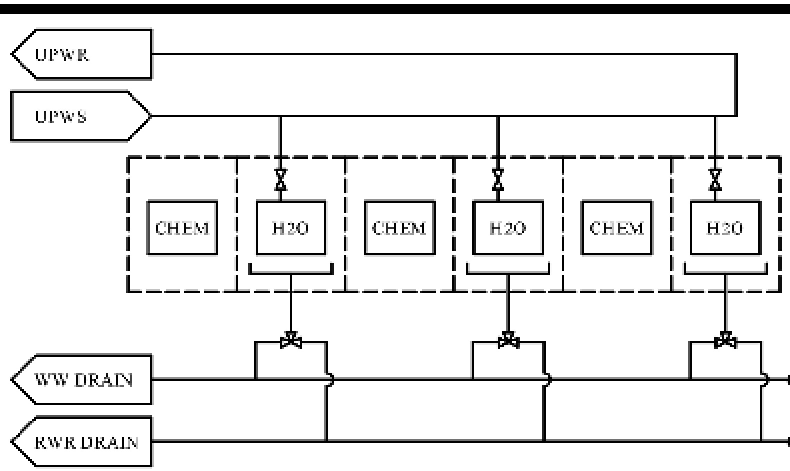

Figure 1. Sink collection.

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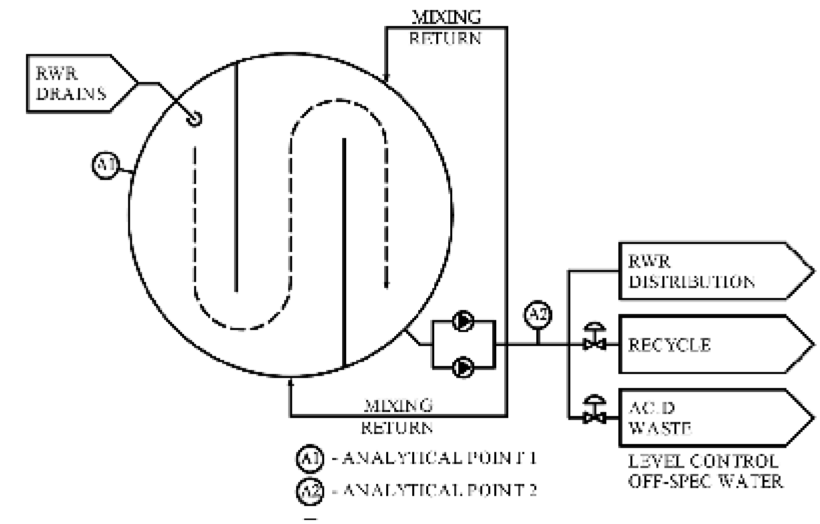

Figure 2. RWR collection and transfer.

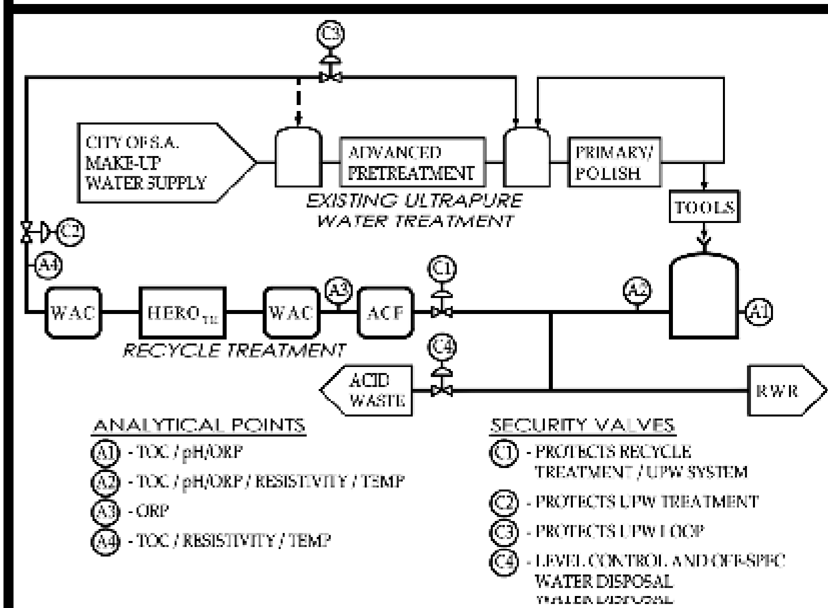

Figure 3. Total organic carbon trend.

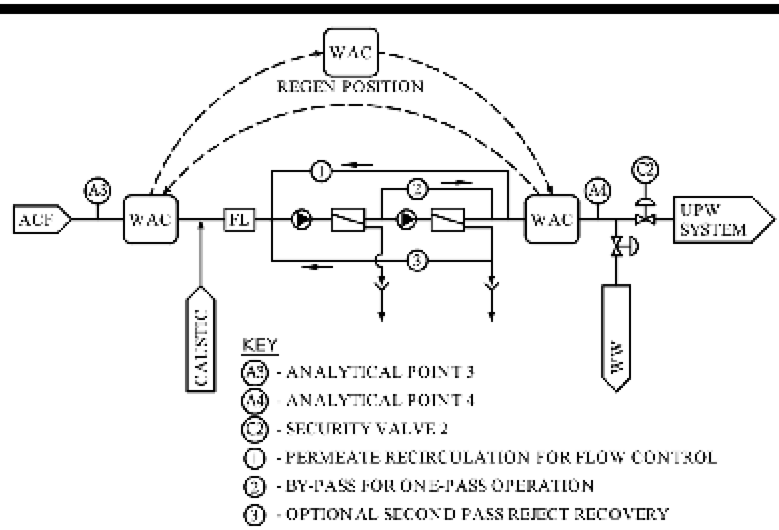

Figure 4. System overview.

schedule needed to stay reasonably controlled, but the system absolutely must not produce water that could hurt the factory's product.

We evaluated the quality of water available from the collection pilot study and the treatment technologies available. Based on this, we believed that a system with high quality product water was feasible, but would require significant care throughout the project. This required the commitment of significant engineering resources from all parties involved. Experienced manpower was hard to obtain because of the extremely aggressive business environment that existed during project execution.

The team evaluated the options for upgraded fresh water versus recycled water and determined that the equipment capital costs for both options would be about the same, but that ongoing costs for purchase and disposal of additional fresh water made that option less attractive. However, we also recognized that the civil, structural, and mechanical costs would be higher for the reclaim/recycle system, partially offsetting the inherent economic attraction. We knew that bringing in a new technology for water recycling would definitely take longer and be more complex than purchasing fresh water capacity to be treated with equipment similar to existing systems. However, we judged that we would still make critical schedule milestones with a recycling project.

We decided to recycle water based on this evaluation and a strong desire to recycle if we could. Reclaim/recycle would meet the commitments of the Philips Environmental policy to be responsible stewards of available resources.

Once we decided to proceed with a water recycling system, potential water treatment system vendors were evaluated quite closely with respect to cost for the proposed system (both capital and operating), manufacturing capacity, engineering experience, and the technical merits of each proposal. In addition, Philips operating experience and manpower availability dictated strict adherence to component and operational specifications. For example, rotating equipment, electrical equipment, controls, wetted surface finishes, and instrumentation are specified with limited opportunity for vendor-suggested alternatives.

The selected equipment must be reviewed from the operations and maintenance (O&M) point of view. This includes a critical review of the process

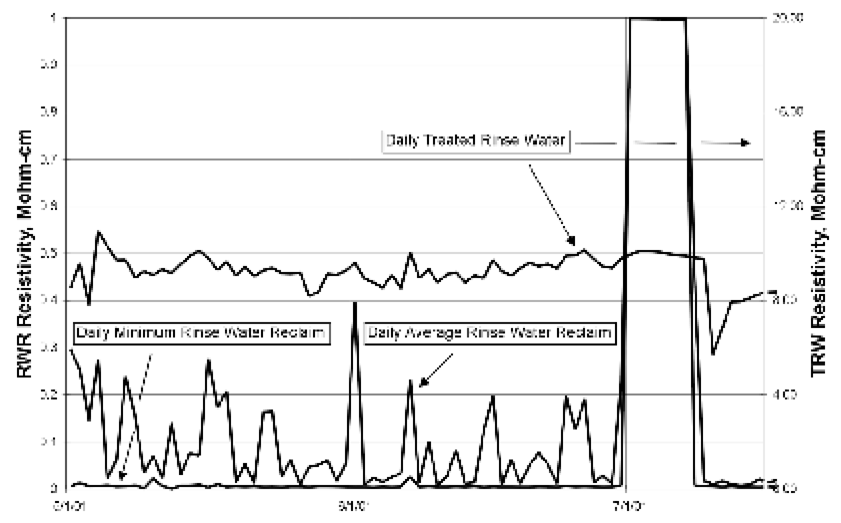

Figure 5. Recycle treatment.

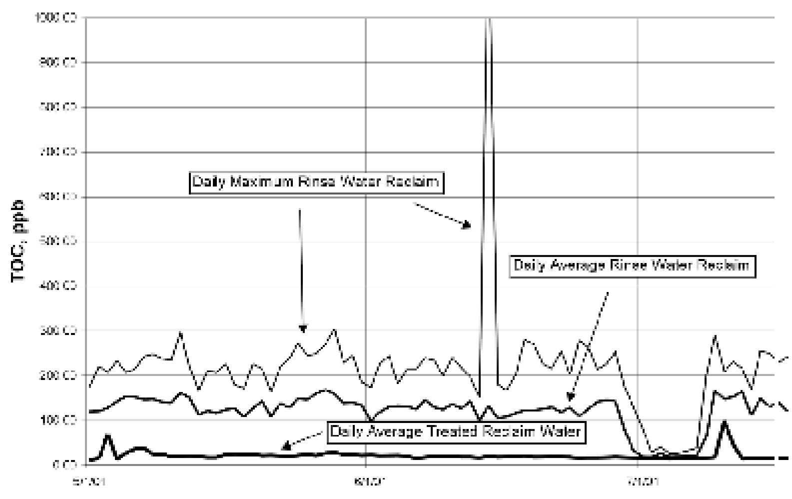

Figure 6. Resistivity trend.

that is finally selected for easy access to all major components for O&M, availability of consumable items as well as spare parts on a short notice. The system should be able to operate in a fairly automatic mode to minimize operator attention. Finally, critical data must be archived and readily available for review to find trends before operational problems require expensive fixes.

Project Implementation and Contract Style

The following steps were used to design, build, install, and commission the reclaim/recycle system:

1. Basic design, including the decision to reclaim/recycle.
2. Preparation of the request for treatment proposal and design of the collection and distribution system for non-treated RWR.
3. Bids from treatment vendors received and evaluated. Construction of civil/architectural improvements begun.
4. Vendor selected. Pilot testing of treatment process.
5. Revised bid accepted. Design and construction of treatment system executed.
6. System installed and commissioned.

The project was executed using a fast-track design process where small packages were released for construction in a series, rather than making a single complete design package that was released at one time.

Treatment vendors were given an option during bidding. If confident that their system could meet all specifications without a pilot test, they could bid the full-scale system, guaranteeing the quality of the final product water. If they were not that confident, they could bid their best estimate of the full-scale system with an option to revise that bid based on pilot testing. Philips reserved the right to reject the revised bid if it was significantly higher than the estimate.

The successful bid included the treatment pilot test described below. Once the piloting results were documented and the proposal was revised and reviewed, the complete full-scale treatment system was awarded. As the project progressed, there was a great deal of engineering scrutiny to verify that the final system would meet all objectives.

The project's implementation activities endured a semiconductor manufacturing industry production increase at its beginning and an industry wide slump in the end. This slump allowed for a relaxation of the schedule at the end of the project. However, it also reduced the demand for high-purity water and the supply of spent rinse water available for the system at commissioning.

History of Existing Pilot Collection System

In December 1997, we started running a pilot reclaim collection system to achieve two goals. First, we wanted to test the quality of the RWR available and project what the quality and quantity would be for a full-scale system. Second, we wanted to verify that this spent rinse water would be a good source of water for the air pollution abatement system.

To accomplish these goals, a 100-gallons per minute (gpm) (378.54 liters per minute) capacity system was built to collect, analyze and distribute the RWR. Based on feedback to a 1997 paper (4), we decided to connect one of each type of wet bench (except solvent strip) to this system. We only connected wet benches that were 200-mm ready, not the 150-mm benches that were scheduled to be replaced. Our reclaim philosophy was to reclaim known good streams. This was accomplished by only connecting to high-purity water baths as shown in Figure 1. Other streams may be acceptable, but they were not included as part of this project.

This system gathered valuable data that was used to specify the full-scale system. Unfortunately, not all of the data gathered by the pilot collection system

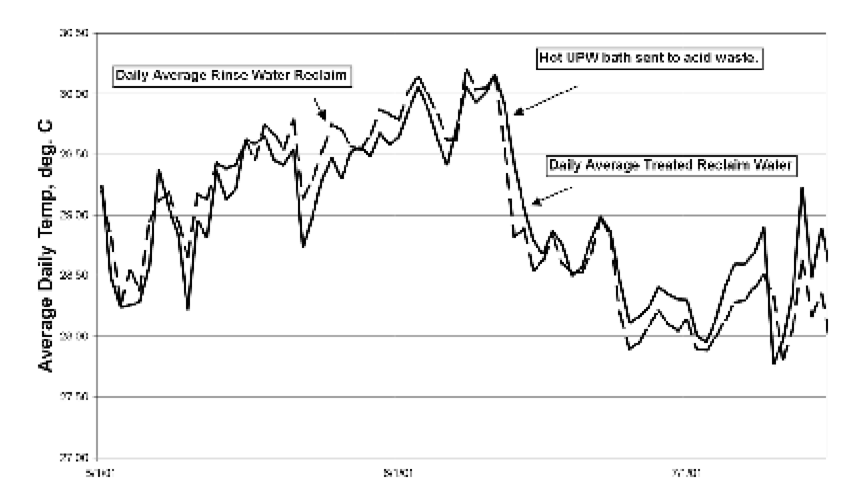

Figure 7. Temperature trend.

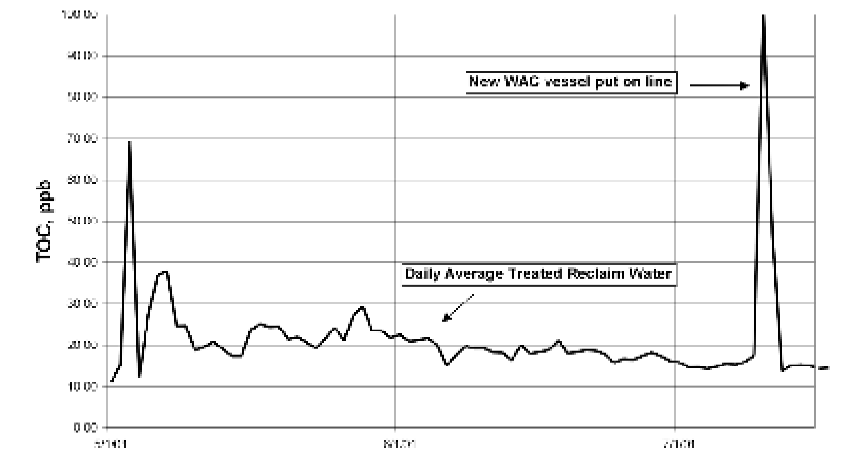

Figure 8. Treated reclaim water TOC trend.

was representative of the full-scale system. During this testing, the majority of production was taking place on 150-mm wafers, not the newer 200-mm wafers. Unfortunately, each batch of larger wafers pulls more chemical into the rinse bath than a batch of smaller wafers. By July 2000, all fab production was taking place on 200-mm wafers. The average resistivity decreased from about 450 kilo-ohm per centimeter (/cm) to less than 200. The average total organic carbon (TOC) measurement increased from 50 to 70 parts per billion (ppb) to more than 100 ppb.

Scope of the Full-Scale System Improvements

The pilot collection system was replaced with a full-scale reclaim collection and distribution system outside the fab. This includes the following primary components:

- Fab-wide gravity collection piping, transfer piping, and associated pipe racks and tunnels to the proposed collection tank.
- Reclaim pit facility designed to house the new and future reclaim equipment.
- A 10,000-gallon open-baffled tank, distribution pumps, distribution piping, analytical, electrical, and controls.
- Distribution piping to non-treated reclaim water customers.

The rinse water reclaim collection and transfer program at Philips is required to serve two purposes: distribution of untreated water to reclaim water customers, and distribution of untreated water within specification to the recycle treatment system prior to recycling to the high-purity water system. A single rinse water reclaim and transfer system to serve both purposes was selected. (Please refer to Figure 2.)

In order to realize a successful reclaim water collection and transfer system, the team felt the following goals must be met:

1. Segregate the clean rinse water from acid waste.
2. Collect and analyze the reclaimed rinse water prior to recycle treatment.
3. Secure the recycle treatment system and high-purity water system from contaminated water.
4. Provide a reliable water source to the non-treated customers.

Figure 1 shows the technique used for segregation of rinse waters at the tools. The installation of a fab-wide gravity collection system for a 12-year-old fab, which was not designed for additional gravity drains, challenged our piping designer. In fact, he was having dreams (perhaps nightmares) about this problem by the time he found a solution.

The design and construction for the drain system took in to account several future drains for chemical waste and water reclaim such that a new "reclaim" hierarchy was formed for the fab. The scheme for half of the building opposed the existing gravity waste hierarchy. The collection piping is Schedule 80 PVC (polyvinyl chloride). Each bay lateral included a clear section of pipe along with a sample valve.

The new drain hierarchy has a relatively flat slope and was high compared to existing piping. Proper venting was considered very important in order for the drain system to avoid an airlock that could result in water backing up into fab equipment. The system was vented to the roof using sloped piping. All laterals more than 15 feet in length are vented. All mains and sub-mains are vented at the high ends and a relief vent is provided in the middle of the drain system.

The team evaluated several schemes for collection of the rinse water:

1. The first scheme was a three-tank system with the water handled by batch. This provides a long response time for analytical equipment and quick clean up from excursions, but is expensive and has several potential failure points.

2. The team agreed to a single open baffled tank as shown in Figure 3. The residence time at design flows is 30 minutes. The open baffle scheme allows maximum dilution of excursions, secures the recycle treatment system in

the event of an unacceptable excursion, and provides a continuous reliable source of water to the non-treated customers. In addition, it was the most economical approach of those we evaluated. The negative for this approach is that a contamination event can take longer to clean up prior to putting the recycle treatment system back on line.

The reclaim collection tank, distribution pumps, and analytical instruments are carefully designed to accomplish the following:

- Provide an early check of the incoming and pH as water is drained into the tank.[a]
- Provide a buffer volume to smooth out the incoming spikes.
- Provide a constant pressure distribution system for non-treated customers and the recycle treatment system feed.
- Provide a final check of TOC, pH, and resistivity.
- Divert to waste in the event of an excursion or contamination.

Figure 4 shows how the tank fits into the overall reclaim/recycle process flow.

Non-treated reclaim water customers include the fab air pollution abatement scrubbers, the fab point-of use hazardous gas burn boxes, and drain flushing water for the chemical mechanical polish (CMP) drains. The reclaim system is critical to fab wafer production and needs to be very reliable. A loss of the reclaim system will stop wafer production.

Recycle Treatment Options

The team evaluated several treatment options according to various quality, cost, and schedule issues. The electrodeionization (EDI) and high-efficiency reverse osmosis (HERO) options are discussed in Table A.

The EDI Option

The EDI process for RWR reclaim was initially the most favored processes. In fact, the original bid documents were based on EDI technology. It offered steady state operation, compatibility with a wide range of pH, and some significant industry installations. The essential process components for this process included the following:

1. TOC destruction by UV with the addition of ozone and/or hydrogen peroxide (H_2O_2).
2. Activated carbon (AC).
3. The EDI system. The specified EDI system included cartridge filters, EDI trains, concentrate pumps, optional brine injection, PVC piping, instruments, and controls.

The High Efficiency RO Option

The HERO process[b] in this application consisted of the following components:

Activated carbon. The rinse water reclaim stream contains hydrogen peroxide, which if not removed would cause degradation of downstream media. To avoid this, AC was included as a first treatment step.

Weakly acidic cation (WAC) resin is used before the RO to remove any calcium and magnesium ions present in the water. Levels above 500 ppb can cause fouling of the membranes. The RO permeate water passes through a WAC vessel, which removes the sodium ions that have been pulled through the RO membrane due to the elevated pH. Use of a polishing WAC vessel provides treated water with very low conductivity.

HERO. The RO part of HERO in this case consists of a double pass of seawater elements[c] operating at elevated pH. Trials, including the treatment process pilot discussed here, indicated a single pass would just meet the specification. Consequently, double-pass RO was preferred.

Based on the analysis given in Table A, the HERO treatment system was chosen.

Recycle Treatment Pilot Study

In order to confirm the performance of HERO on Philips spent rinse water a trial system was sent from the UK to the Philips site. The trial rig consisted of an aerated collection tank, two WAC resin columns, one with AC on top and a single 2.5-inch RO membrane housing.

Initial trials were completed using a brackish water element; however, the rejection from these elements was felt to be insufficient at the water temperatures experienced. As a result, a second set of trials were completed using a seawater element that gave the required rejection.

The results from the seawater element trials indicated that HERO would achieve on average better than 93% rejection of incoming TOC on a log (Ln)-mean basis. Rejections of up to 96.7% were observed under some conditions.

The Ln mean rejection is calculated as follows (Equations 1 through 4) for a water with 200-ppb feed TOC (the anticipated normal maximum level):

Concentration Factor,

$$CF = 1/(1 - Y_H) \quad \text{Eq. 1}$$

where Y_H is the hydraulic recovery of the system

For example, 95% recovery gives a CF of 1/1-0.95 = 20

$$Y_H = \text{Product flow/ Blended flow} \quad \text{Eq. 2}$$

$$Y_H = 0.95$$

Ln mean concentration factor at membrane surface= $\ln(CF)/Y_H$ Eq. 3

The Ln mean factor is therefore:

$$\ln(20)/0.95 = 3.15$$

3.15 x incoming feed

$$= 3.15 * 200 = 631 \text{ ppb} \quad \text{Eq. 4}$$

At 93% rejection, this equals:

$$631*(1-0.93) = 44.15 \text{ ppb}$$

The second pass operating at anything above 86% rejection would give 20 ppb in the product. At the best rejection (96.7%) observed during the trials, a product TOC of 21 ppb would have been achieved using a single-pass RO.

Full Scale system design features. The recycle treatment flow scheme shown in Figure 5 was developed by the water treatment vendor for the full scale system. This was based on the results from the various site trials and Philips requirements for the final plant during the design stage. The purpose of each section of plant has already been discussed.

To cope with a variable feedwater flowrate, the RO was designed to run with a continuous flow of 180 gpm through the RO membranes while adjusting the amount of permeate (Line 1) that is recycled to the RO inlet. This maintains the required constant feed flow. By doing this, the plant is capable of running with anywhere between 50 gpm and 180 gpm feed flow. Future expansion has been allowed for in the design that would take the system up to a maximum capacity of 225 gpm.

All pumps in the system are fitted with variable frequency drives, allowing the internal RO skid flowrate to be adjusted if required. The pumps automatically adjust to maintain the target flowrate, so that temperature has a minimal effect on membrane flux. We have found that the system also operates well at a lower flowrate of 145 gpm, saving power and decreasing the water temperature slightly.

The RO system was designed with the ability to run in either single- or double-pass mode (Line 2). Reject from the second pass can be sent back as feed to the first pass (Line 3), giving an overall water recovery of 95% on a twin-pass RO. Due to Philips concerns over metallic components in the system, the second-pass reject can also be sent to drain to prevent any potential contamination risk from the high-pressure stainless steel pipe work.

Any of the three WAC vessels can be operated in the pre- or post-RO position. During normal operation, the polishing vessel, when exhausted, is valved to be in front of the RO. The old lead vessel resin is then taken away for regeneration. Once regenerated, the resin is returned to the vessel and placed on line as a polishing vessel.

Report on System Performance

Low flow conditions. The most striking issue during commissioning and steady state operation was the lower-than-expected flow available to the RWR system. This was due primarily to the industry wide slowdown that started in the fourth quarter of 2000 and deepened as the first and second quarters of 2001 progressed. Since the factory was producing less, we were using less water.

Unfortunately for the reclaim system, most of the resulting reduction in water consumption took place at the wet benches, which have low flowrates when not being used. During the time covered in the trend graphs, the recycle treatment system was working at 50% to 60% of its capacity.

Incoming quality. As mentioned above, the quality of incoming water did not match the quality levels predicted by the pilot testing. As production levels in the factory have increased, the quality has decreased in terms of incoming resistivity (Figure 6). The TOC spikes are larger and more frequent than the pilot results indicated (Figure 3). Another significant issue for full-scale system operation has been that the incoming water temperature was significantly higher than expected (Figure 7). We have reduced the flow of hot DI water baths into the reclaim system to reduce the temperature. In its current configuration, we cannot use the treated reclaim water if the temperature is above 30 °C.

Product quality. Initial product quality has been very good with the exception of TOC. The product resistivity has been very good (Figure 6). The TOC has been high because of high elution of organic molecules from the polishing WAC unit (Figure 8). In a matter that surprised and delighted the project team, we have found that the system can produce excellent quality of water even with very high levels of incoming IPA. We have spiked in more than 1,000 ppb of isopropyl alcohol (IPA) (as C) and seen 98% rejection of IPA.

Brine Concentration for Existing RO Trains

The makeup RO system is a single-pass, two-stage operating at roughly 75% recovery. A extension of the system to recover part of the brine stream was built. This was comparatively straightforward, requiring only additional RO tubes, low-pressure/high-rejection RO membranes, piping, and accessories. A new scale inhibitor was required to allow the "third stage" RO to operate in some instances up to approximately 50% recovery, increasing the overall recovery to roughly 87%[d]. This system does not require additional RO high-pressure pumps, since the RO reject exiting from the primary RO trains is available at sufficient pressure.

Lessons Learned

When we looked back at the successes and challenges of this project, we saw that more planning and more engineering resources would have been extremely beneficial. However, in the business climate that prevailed when the system was designed and built, planning time and engineering resources were not easily available. In future similar projects, we hope to put more time and effort in the process piloting portion of the project since that has great leverage in affecting the system design and cost.

Temperature is very important to water recycling system performance. In addition, the effect of "closing the loop" in water recycling systems aggravates high water temperature conditions. When doing the piloting study, we did not grasp how much of the water we collected was from hot DI baths and assumed that high temperatures seen on occasion were due to low flow/high recirculation rates in the collection system. In fact, the water temperature would actually be more than 32 °C if we collected all of the hot deionized (DI) rinses during the summer months. This effect could have been moderated if we had installed our activated carbon indoors and away from the hot Texas sun and warm average outdoor temperatures. Also, heat exchangers for the process water would be quite useful in keeping the system at steady state.

Single-pass RO is apparently good enough for this application. We found that one pass of RO removes essentially all of the organic contaminants presented to the system. Obviously, single-pass RO is less expensive to build and operate.

Unfortunately, money and resources for a detailed system characterization and startup were not available at the time needed. A mass balance constructed at several operating conditions would be beneficial as part of the commissioning of the system. Our mode of operations at that point of the project was to find an acceptable running condition for the conditions we had. During trouble shooting of the system in the years to come, there will be nagging questions about whether the system has changed or not.

We have found that the WAC resin we used elutes significantly more TOC than would be expected from high-purity water grade strongly acidic cation resin. Regeneration of the WAC resin improves its performance in a manner similar to that of resins more commonly seen in semiconductor high-purity water plants. However, continuing high elution organics makes the WAC resin undesirable, unless there is RO downstream to clean the water up again.

Also, we have found that the vast majority of issues reducing the amount of water reclaimed have their origin in the maintenance groups who care for the wet benches. Education in the form of training sessions describing the reclaim system and feedback on the amount of water lost due to improper handling of the cleaning chemicals has significantly decreased the number and severity of excursions.

In addition to clear lateral sections, clear pipe at each drop from a water bath is a good way to indicate that a given bath is or is not connected to the reclaim system. As money becomes available, we hope to go back and in-

TABLE A
Recycle Treatment System Options Comparison

System Components	*Capital Cost*	*Operating Cost*	*Efficiency*	*Treated Product Quality*	*Equipment Reliability*	*Ability to Handle Excursion*
EDI (RFP Basis of Design) UV/ozone or H_2O_2 Activated carbon Cartridge filtration Chemical injection EDI	high	high	very good	per specs	fair	unknown
HERO Activated carbon Weak acid cation Cartridge filtration Chemical injection Reverse osmosis Weakly acidic cation	medium	high (two-pass)	very good	better than specs	good	good

stall these clear sections.

We spent a great deal of time and effort to give the TOC instruments at the collection tank adequate time to respond in case the recycle stream needed to be diverted. We have found that TOC instruments are fast enough now that special engineering of the tank was not needed.

Finally, we were fortunate to find a window of opportunity to implement a water reclaim retrofit. We were prepared to execute with pilot data available and system programming basically complete when the project started. That preparation was key to obtaining approval and funding.

Acknowledgements

The authors wish to thank those who have contributed so much to the success of this project. Prominent among those are the facilities operations group at Philips San Antonio, Philips Management, and our colleagues in the industry who have been willing to share their insights and experiences.■

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3. The Philips Environmental policy is available for download at: http://www.semiconductors.philips.com/profile/env/policy/.
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Endnotes

[a]TOC instrumentation was supplied by Sievers Instrument Co. (now known as Ionics Instruments), Boulder, Colo.

[b]The HERO process was supplied by Christ Water USA, Vancouver, WA in partnership with Kennicott Water Systems UK Ltd.

[c]RO membranes provided by Dow Liquid Separations, Midland, Mich.

[d]Antiscalant supplied by King Lee Technologies, San Diego, Calif.

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