Utility Consumption Characterization Protocol for Semiconductor Tools

International SEMATECH
Technology Transfer # 00043939A-ENG

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Abstract: This document contains a measurement protocol to characterize power and energy requirements of semiconductor tools. The protocol addresses specific requirements for measurements and provides electrical fundamentals for data interpretation and analysis. A field guidance document is also included for conducting power, exhaust, and water measurements at the tool.

Keywords: Electric Current, Manufacturing, Measuring Instruments, Power Consumption, Procedures

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1 EXECUTIVE SUMMARY

This document specifies the minimum set of measurements and configuration considerations needed for a power and energy audit of a semiconductor processing tool. It also defines a method to determine energy per wafer area on any size or type of processing tool and suggests a format for data presentation. A field guidance document includes procedures for conducting power, exhaust, and water measurements at the tool.

2 POWER MEASUREMENT PROTOCOL

A comprehensive characterization of the power/energy requirements of a tool requires many different measurements. Although this protocol does not specify a particular power analysis instrument for any of the measurements, the measurement tool selected needs to perform all measurements specified. Instruments that cannot perform the measurements in less than 250 milliseconds (mS) should not be used because they will not be able to adequately characterize the dynamic nature of the electrical load presented by processing tools. If possible, a measurement system capable of performing the required measurements on a cycle-by-cycle basis should be used, assuring a complete description of the power demand.

2.1 Tool Configuration

The primary goal of a power audit is to calculate the energy per wafer pass and the power quality of the tool and sub-components. The proposed tool configuration and process needs to be defined by the individual product group responsible for that tool. When comparing tools of different wafer sizes, such as 200 mm and 300 mm, the process should be chosen so that the end physical result of the wafer being processed is the same. The second goal is to provide electrical data in a format that allows a better design of future semiconductor fabs.

The power and energy requirement for this tool configuration will be measured at the power line drop to the tool. When multiple power drops are used, each drop should be measured separately. The proper method for combining and reporting the data retrieved from multi-drop measurements is outlined in a later section.

General forms for documenting the tool and process chosen are included in the appendices. This form should be used to describe the test conditions. The information required includes the mainframe or model, process chambers, tool operation, pumps, water heaters, test operator, test date, location, etc. The equipment name and model numbers need to be in this record. Other data will need to be added for a full description of the system configuration according to the system. This information should be archived with the final test record.

2.2 Process Selection

The test process, or tool operation, should be chosen to best represent a common customer process. The data should be collected on two full cassettes of wafers. Appendix D includes a guideline for gathering data about the test process. This information should be gathered and archived with the final test record. Because of the nature of the equipment being tested and the cost of wafers (especially 300 mm wafers), it may not be possible to run two full cassettes; however, a sufficient number of wafers must be run to get statistically significant energy per wafer or average power data. Many process tools have a very consistent operating energy profile.

For a complete characterization, the data capture time should include processing on two entire wafer cassettes, from tool startup to shutdown. The wafer cassettes should be placed in the system at the normal point in the tool operation. This will allow for a system-level power audit as well as information about energy usage per wafer. If the machine is allowed to go into an idle state before wafer processing starts, information about the idle power usage of a tool may also be acquired.

2.3 Required Power and Energy Data

The final audit report on a tool should include the data in Table 1.

Table 1 Required Data for Tool Power and Energy Characterization

Measurement
Average kVA
Max kVA
Average kW
Max kW
Average P.F.
Min P.F.
Total kWh
Average kWh per wafer
Average kW at idle
Per Phase Current Distortion

In addition to this data, other information should be included in graph format. Table 2 shows the information that needs to be plotted versus time.

Table 2 Data to Be Presented in Graph Form vs. Time

Measurement	Type
KVA	Per ϕ and total
POWER FACTOR	Per ϕ and total
KW	Per ϕ and total
CURRENT	Per ϕ and total
VOLTAGE	Per ϕ and total
CURRENT DISTORTION	Per ϕ
KVAR	Per ϕ and total
NEUTRAL CURRENT	On 3ϕ

The information required in Table 2 is derived from existing customer specifications as well as industry trends towards a full disclosure characterization of an industrial load.

2.4 Measurement Instrument Requirements

The measurement instrument chosen for the power measurement protocol must be a single digital instrument capable of making all of the required measurements. The instrument should be able to record at least 48 hours of data on internal storage media; the reported data interval should be less than 30 seconds. The measurement information should be easily retrieved for analysis at a later date.

3 POWER MEASUREMENTS

3.1 Measurements and Measurement Accuracy

Table 3 summarizes the power measurements, accuracy, and type. With this set of measurements along with a neutral wire current and per phase current distortion measurements, a good characterization of a tool is possible. Accuracy for any individual measurement should be no worse than 5%.

Table 3 Power Measurement Summary

Measurement	Type	Accuracy
Apparent Power (VA)	Per ϕ and Total	5%
Reactive Power (VAR)	Per ϕ and Total	5%
Real Power (W)	Per ϕ and Total	5%
Power Factor	Total	5%

3.2 Apparent Power

Apparent power is the sum of real and imaginary power in an AC electrical system. Apparent power measurements need to include information on all three phases as well as total apparent power on separate plots. The accuracy specification was determined by sampling the field of available measurement systems.

3.3 Reactive Power

Reactive power for sinusoidal waveforms is defined as the imaginary part of apparent power. The unit of reactive power is the volt-ampere reactive (VAR). The measurement device needs to measure the reactive power for each individual phase as well as the total reactive power drawn by the load on separate plots.

3.4 Real Power

Real power for sinusoidal waveforms is defined as the real part of S. The unit of real power is the Watt (W). The measurement device needs to measure the real power for each individual phase as well as the three-phase real power absorbed by the load.

3.5 Power Factor

The power factor relates the amount of real power and reactive power in a system. The measurement device must be able to correctly report the power factor even for highly distorted current and voltage waveforms. The power factor of a system can also be described as a measure of the work-producing power delivered to a system.

The power factor is reported as a unitless number between 0 and 1, with a lagging or leading descriptor. The terms lagging and leading refer to the type of load. Loads with a capacitive reactive component are leading, and loads with an inductive reactive component are lagging. Some systems report a negative power factor, which usually indicates a leading (capacitive) load, while a positive number would indicate a lagging (inductive) load.

4 VOLTAGE MEASUREMENTS

4.1 Meter Type

The voltage measurement should be made with a digital instrument capable of reporting the true root mean square (RMS) value of the voltage waveform. The power meter should support and report voltage measurements simultaneously with all other measurements. Analog, moving-coil, electrodynamics, or other types of voltage measurement are not suitable for applications where a full characterization of a load is necessary.

4.2 Accuracy

All voltage measurements should be made with an accuracy of 5% or better.

5 CURRENT MEASUREMENTS

5.1 Meter Type

The current measurement should be made with a digital instrument capable of reporting the true RMS value of the current waveform. The power meter should support and report voltage measurements simultaneously with all other measurements. Analog current measurement devices are not suitable for applications where a full characterization of a load is necessary.

5.2 Accuracy

All current measurements should be made with an accuracy of 5% full scale or better. Both the measurement instrument as well as the current transformer (CT) required for measurement must be included in the accuracy calculation. The total accuracy is calculated using the geometric mean of the two instruments:

$$\% Accuracy = \sqrt{A_1^2 + A_2^2} \, ,$$

where A_1, and A_2 represent the accuracy of the two instruments, respectively.

5.3 Transient and Peak Current Measurements

The measurement instrument should be capable of measuring peak current with better than 10% full scale accuracy.

5.4 Current Transformer Frequency Response

The current transformer chosen should have a measurement bandwidth equal to or greater than the frequency of the highest order harmonic to be analyzed. Table 4 shows the necessary upper frequency limit corresponding to the harmonic number.

Table 4 Current Transformer Frequency Response

Upper Frequency Limit	Highest Harmonic Measured
3,000 Hz	50
3,780 Hz	63
6,000 Hz	100

The values given in Table 4 also allow this protocol to be used in areas where the fundamental distribution frequency is 50 Hz.

5.5 Current Transformer Ratings

Current transformer selection depends on measured current value. To achieve the highest accuracy possible with a particular current transformer, the current should be between 10% and 100% of the rated full-scale value. If the measured current is outside of these limits, a different current transformer should be chosen.

5.6 Current Distortion Measurements

High current harmonic distortion causes several problems in specifying facility power distribution. Non-sinusoidal waveforms can cause equipment malfunction, undesirable operation, and higher required supply capability.

To provide complete disclosure of the power requirements of the tool, current harmonic distortion needs to be measured with an instrument that complies with IEEE 519.

Current distortion is reported as a percentage. Total harmonic distortion (THD) is usually appended to the figure.

6 NEUTRAL WIRE CURRENT MEASUREMENTS

If a three-phase wye (“y”) distribution method is used, a full power audit of a tool requires that neutral wire current measurements must be made. Large magnitude neutral currents induced by the tool may cause unexpected equipment operation and failures. Customers must know the magnitude of the current imbalance drawn by the tool as well as neutral currents to accurately specify facility distribution. If a single-phase distribution system is used, neutral current should be measured.

6.1 Meter Type

The neutral current should be measured with a digital instrument that reports neutral current in true RMS fashion. The power meter should support and report voltage measurements simultaneously with all other measurements.

6.2 Accuracy

All current measurements should be made with an accuracy of 5% full scale or better. Both the measurement instrument as well as the CT required for measurement must be included in the accuracy calculation. The total accuracy is calculated using the geometric mean of the two instruments:

$$\%Accuracy = \sqrt{A_1^2 + A_2^2},$$

where A_1, and A_2 represent the accuracy of the two instruments, respectively.

6.3 Current Transformer Ratings

The selection of a neutral current transformer depends on the measured current value. To achieve the highest accuracy possible with a particular current transformer, the current should be between 10% and 100% of the rated full-scale value. If the measured current is outside of these limits, a different current transformer should be chosen.

7 REAL ENERGY MEASUREMENT

Real energy consumption is defined as Watt-hours. It can be calculated from a kW consumption curve. The formula is as follows:

$$Energy = \int kW_{3\theta Avg}\, dt$$

Figure 1 is a sample plot showing energy usage and power consumption versus time.

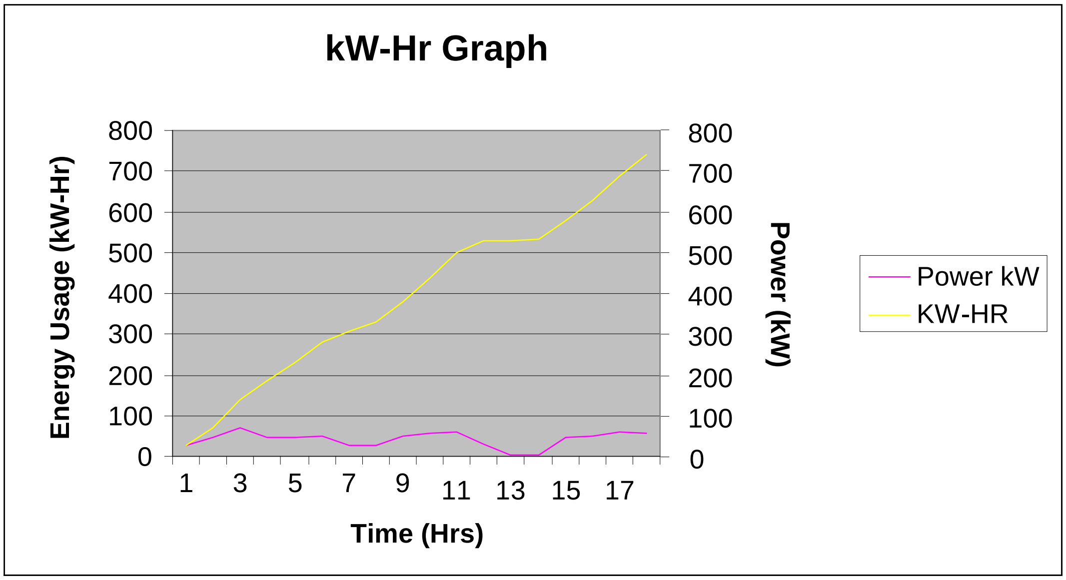


Figure 1 Example kW Consumption

In Figure 1, since the unit of time is hours, the total kWh billed by the utility would be

$$\text{Energy (kWh)} = \text{Average Power (kW)} \times \text{Process Duration (h)}$$
$$742kWh = 41.2kW \times 18h$$

7.1 Per Wafer Area Energy Calculation

The energy requirements on a per wafer basis should be calculated using the following formula:

$$\text{Process Duration (h)} * \text{Average Power (kW)}/(\text{Number of Wafers}* \text{Surface Area of Wafer}(cm^2)) = \text{Per Wafer Energy Related to Surface Area} (kWh/cm^2)$$

And

$$\text{Average Power (kW)} = \text{Energy (kWh)}/\text{Process Duration (h)}$$

Wafer processing time is defined as starting when the first wafer is loaded into the first process chamber until the last wafer is removed or until any post-processing clean steps are completed, whichever is longer. This includes idle time and all intermediate steps in the wafer processing sequence. These steps are included since they are necessary for processing.

7.2 Process Power Factor Calculation

During wafer processing, the average power factor should be calculated. The time used should be the same as the per wafer real energy calculation. Utilities will often impose extra charges on loads with power factors less then 0.85 or 0.80. The amount of the charges and the minimum power factor required for these fines vary from utility to utility and the country of service. Power factor is usually described as lagging or leading. The terminology refers to the phase angle of the current in the system with respect to the voltage. If the phase angle is 45 degrees with the current lagging the voltage, then the factor is 0.707 lagging.

7.3 Startup Real Energy Calculation (Optional)

The energy requirements for a processing tool startup should be calculated using the following formula:

*Tool Startup Time * Average kW Consumption During Tool Startup = Startup Energy*

The tool startup time is the time at which the tool is turned on until the first wafer is loaded in the chamber. This process should occur according to the standard startup and shutdown procedures for the tool under audit. Peak current values must be recorded and reported.

7.4 Shutdown Real Energy Calculation (Optional)

The energy requirements for a processing tool should be calculated using the following formula:

*Tool Shutdown Time * Average kW Consumption During Tool Shutdown = Shutdown Energy*

The tool shutdown time is the time from the removal of the last wafer from the chamber until power can safely be turned off. This process should occur according to the standard startup and shutdown procedures for the tool under audit.

7.5 Idle Power Measurement

The average idle power used by the tool should be measured immediately before or after the process power measurements. Idle power assumes that no wafers are being processed. The tool should be configured to be ready to process 1 minute after wafer loading. The idle power measurement should be long enough to cover any normal variations in a standby mode, such as heaters cycling to maintain temperature, but not less than 10 minutes.

7.6 Process Tool Subcomponents

Subcomponents such as pumps, radio frequency (RF) power supplies, etc. must be characterized in the same manner as the process tool. Take the same measurements specified in Table 1. Complete the energy per wafer pass in the same manner as the process tool. All subcomponent measurements should include neutral wire current measurements, if present.

8 MULTIPLE DROP SYSTEM MEASUREMENTS

Processing tools may have multiple drop power distribution systems. This distribution method requires that either multiple measurement runs or several measuring instruments are used. Multiple measurement runs will require proper post-processing for reports.

8.1 Time Referenced Data

Multiple measurement runs will require proper post-processing for reports. Time-dependant (referenced) data, for example current (RMS, peak) *plotted over time*, must not be mathematically summed with data measured at another drop. The inability to perfectly align events or sample periods between two or more measurements could result in large errors. Display plots from each drop separately.

Do not sum maximum and minimum values unless they are used for worst-case consumption information.

8.2 Averaged Data

Averaged or total data can be combined. For example, if the average Phase A current of the first drop is 100A RMS and the second drop is 40A RMS, it is valid to say that the total phase A current is 140A.

9 CALIBRATION OF THE MEASUREMENT SYSTEM

The measurement system should be calibrated on a yearly cycle at minimum. The manufacturer’s recommendation should be followed and a metrology laboratory used for the calibration. The current and potential transformers must also be calibrated.

A calibration sticker should be attached to the measurement instrument indicating the calibration due date. The instrument must not be used for protocol measurements if the date has passed. Table 5 shows a standards compliance matrix.

Table 5 Standards Compliance Matrix

PMP Section	Type of Measurement	ASTM E 929-83	IEEE 120-89	IEEE 519-1992	73/23/EEC
3.2	Apparent Power	Yes	Yes	N/A	N/A
3.3	Reactive Power	Yes	Yes	N/A	N/A
3.4	Real Power	Yes	Yes	N/A	N/A
3.5	Power Factor	Yes	Yes	N/A	N/A
4.1	Voltage (RMS)	N/A	Yes	N/A	N/A
5.1	Current (RMS)	N/A	Yes	N/A	N/A
5.3	Current (Peak)	N/A	Yes	N/A	N/A
5.6	Current Distortion	N/A	N/A	Yes	Yes
6.1	Neutral Current	N/A	Yes	N/A	N/A
7.0	Energy Measurement	Yes	Yes	N/A	N/A

Table 6 is the compliance matrix of commonly available equipment.

Table 6 Equipment Compliance Matrix

April 1998

Equipment	Manufacturer	V	I	kWh	kW	kVA	kVAR	P.F.	T.H.D.	Voltage Unbalance	Current Unbalance
Power Recorder	Reliable Power Meters	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Yes	Yes
PM3300CE	Voltech	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Unk.	Unk.
PM3300CE	Voltech	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Unk.	Unk.
77001ON	Power Measurement	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Yes	Yes
WT2030	Yokogawa	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Unk.	Unk.
4300	Dranetz	3 Phase, Total	3 Phase, Total	No	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	External Card Required	No	No
3030A	BMI	3 Phase, Total	3 Phase, Total	Unk	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Yes	Yes
ACE 2000	CPM	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	Yes	Yes
D6000	LEM	3 Phase, Total	3 Phase, Total	Yes	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	3 Phase, Total	No	No

Table 7 Equipment Compliance Matrix

April 1998

Equipment	Harmonics	Current Trans.	Voltage Trans.	# of Simultaneous Measurements	Communications	Neutral Current	Web Page Address
Power Recorder	63rd	Yes	Yes	All parameters, 1 per second.	Ethernet, RS-232, Parallel Port	Yes	www.reliablemeter.com
PM33000CE	99th	yes	Yes	Unk.	IEEE488, RS-232	No	www.voltech.co.uk
77001ON	60th	Yes	Yes	Update Rate: once per cycle and once per second	Ethernet, LonWorks	Yes	
WT2030	50th	Yes	Yes	36 in 250 mS	GPIB, RS-232	No	www.yca.com
4300	50th with card	Yes	Yes	All parameters, 1 per second	Proprietary Memory Cards	Yes	www.denetz.com
3030A	50th	No	No	Unk.	Modem, or 720kB 3.5” Disk	Yes	www.dranetz-bmi.com
ACE 2000	50th	Yes	Yes	Unk.	RS-232, Ethernet, Parallel Port	Yes	www.cpm-eletronics.com
D6000	99th	No	No	Unk.	GPIB	Unk.	www.lem.nl

10 PROTOCOL TEST MANUAL

This document describes the details and background information necessary for performing a power audit on semiconductor processing tools. A short review of three-phase power concepts explains terminology and concepts needed to correctly interpret the data recorded during a power audit.

10.1 Three Phase Power Review

In a three-phase power distribution system, power is usually delivered to a load using either a three-wire delta (Δ) or a four-wire wye system. The voltage delivered to each of the terminals is 120 degrees out of phase with the other voltages in the system. Each phase is traditionally given a one letter designation of A, B, or C. Positive sequence systems are labeled (clockwise) ABC, and negative sequence systems are labeled ACB.

Figure 2 shows wiring diagrams for the two systems. For meters that require phase-to-phase voltage references for measurements, this notation does matter and can affect results. The Dranetz/BMI Power Platform is one such meter; consult the documentation provided by the manufacturer for further information.

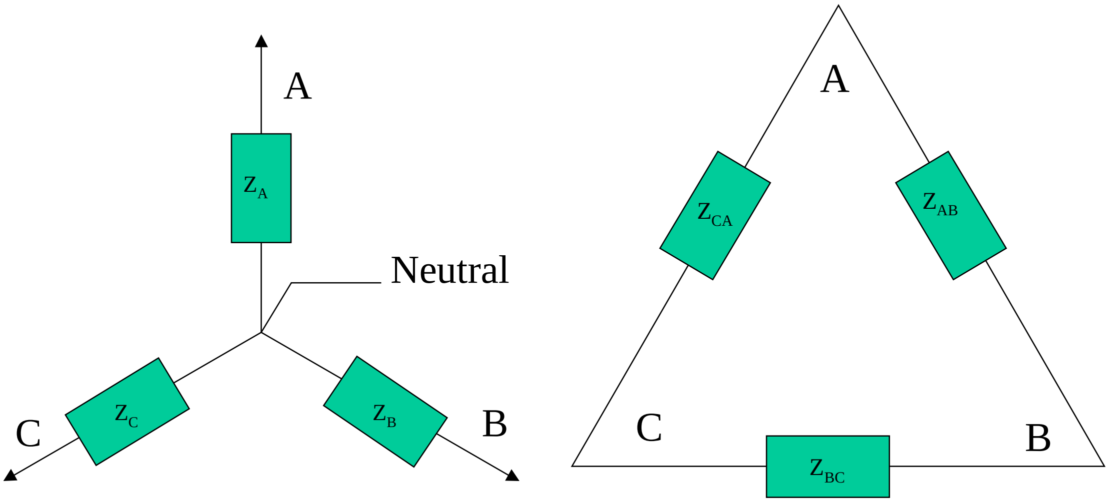


Figure 2 Wye and Delta Configuration Three-Phase Loads

For three-phase wye systems, voltage is referenced from phase to neutral while delta systems are referenced from phase to phase. For example, V_{AN} is the voltage from phase A to neutral in a wye system while V_{AB} is the voltage from phase A to phase B in a delta system.

10.1.1 Three-Phase Loads

In an ideal three-phase distribution system, the loads presented to each phase of the utility supply are perfectly balanced. This results in three-phase currents that are 120 degrees apart summing to 0. In the real world, however, loads are rarely balanced; it is not uncommon to see 10% variations in load impedance from phase to phase. The result is that in a wye system, current will flow in the neutral wire back to the source (utility) or in a delta system, circulating current will flow in the supply transformer.

Real world loads also present non-resistive components to the utility. If the load is inductive, the current waveform lags the voltage waveform and is said to be a lagging current. Conversely, capacitive load current waveforms lead the voltage and are called leading. This also relates to a measurement called power factor (see the next section).

Non-linear loads present certain issues for three-phase power systems. Non-linear loads are loads that cannot be described by using only inductors, resistors, and capacitors. These loads include adjustable speed drives for motors, switching power supplies, and switching heating networks. These loads draw current waveforms from the utility supply that are not sinusoidal and may contain extremely high levels of current harmonics.

10.1.2 Power and Power Factor

For three-phase systems, power can be reported several ways: apparent power, reactive power, and true (or real) power. True power is simply the power drawn by the resistive portion of the load. Reactive power is actually currents drawn by the reactive portions of the load. This power is not dissipated in the end load, but it does require greater service capability from the utility supply. The third method of reporting power is apparent power. This is actually the geometric mean of the reactive power and real power. The following formula is one way of explaining the relationship between these quantities:

True Power = P (Watts)
Reactive Power = Q (VAR)
Apparent Power = S (VA)

$$S = \sqrt{P^2 + Q^2}$$

The different representations of power are also designated by power factor (P.F.). Power factor is related to the phase angle between the voltage and current waveforms as well as the total harmonic distortion in the current waveform. The following formula can be used to relate apparent power (S) and true power (P):

$$P = P.F. \times S$$

Power factor is reported as a real number between 0 and 1. A P.F. of 0 indicates a completely reactive load, while a P.F. of 1 is a resistive load. Utilities often charge extra for power delivered into low power factor loads. This is one reason why some large-scale utility customers spend money to correct the power factor at their facility. This is accomplished by installing special equipment to control the phase angle of their complex loads and filters for controlling current harmonics.

10.1.3 Current Total Harmonic Distribution

The current waveform of a linear load is a perfect sine wave. While the current waveform may not be in phase with the voltage waveform, indicating a complex load, the sine wave is undistorted. In the semiconductor processing tool industry, relatively few loads will be purely linear. Most loads will have a non-linear component generating harmonics in the current waveform. These loads most often are some kind of switching power supply or variable speed drive.

Current distortion is a concern in power distribution because it can create many different problems for different types of equipment. For instance, transformers are rated based on heating from undistorted load currents. When highly distorted loads are used with a transformer, the current distortion creates increased heating from hysteresis, eddy currents, and skin effect. Motors will also suffer as harmonics generate heating, which gradually wears down insulation in the windings, shortening motor life.

10.2 Equipment Required

10.2.1 Current and Potential Transformers (PTs)

10.2.1.1 Current Transformer (CT) Requirements

It is best to have multiple types of current transformers. The common models available are either the flexible or standard clamp-on types. The flexible CTs have the advantage that they can often be installed at locations where space is at a premium. Inside electrical equipment spacing between buss bars may be less then a few inches. Clamp-on CTs are usually easier to install at the equipment if there is enough space. Clamps are also suggested if installation is required while the circuit is still energized. The CTs should not be rated for less than the expected maximum currents.

10.2.1.2 CT and PT Issues (RF Interference)

In one previous test, it was discovered that the RF generators used for semiconductor processing (13.56 MHz) caused interference with the flexible current transformers used for testing. The result was a drop in the reported power usage of the semiconductor tool while the RF generators were turned on. The drop was significant, around 80%, and was an error. When the flexible transformers were replaced by clamp-on current transformers, the power was reported correctly.

It is not known whether the problem was due to RF leakage or low noise rejection of the flexible current transformers. The problem has not manifested itself with systems that do not use RF generators. It is suggested that all systems containing high power RF sources use clamp-on current transformers.

If a problem is found, it might be helpful to use an RF leakage probe to determine if the interference is due to radiated RF fields or high frequency current harmonics induced in the supply.

10.2.1.3 Safety Equipment

Because of tool operation and utilization constraints, it is sometimes necessary to connect measurement equipment to the power distribution box with the electrical system energized. In this case, it is necessary to follow all local safety procedures.

At a very minimum, all metallic jewelry should be removed and safety equipment should be worn. For the 208 V distribution commonly found in the semiconductor industry, a pair of Class 1 rated electrical insulating gloves should be worn. Local regulations may also require an insulating floor mat, a working partner, and a removal hook.

Approved insulating gloves consist of rubber insulated gloves protected by leather outer gloves. The leather outer gloves are designed to be shorter than the rubber gloves in case they get wet. The rubber insulators should never be used without the leather protectors. Before each use, the rubber gloves should be inspected for cuts, scrapes, and any other physical damage, as any damage will result in lower insulating ratings.

10.3 Preparation

10.3.1 Tool Inspection

The semiconductor processing tool should be inspected before testing. If startup information is needed, the measurement instrument will need an A/C outlet that is not powered by the tool distribution system. Otherwise the convenience outlets supplied on some tools are suitable.

Often several of the safety shields must be removed to hook up the current and potential transformers. Precautions should be made so that this removal can be made safely and no one will be able to accidentally contact any exposed, energized conductors.

10.4 Test Outline

10.4.1 Equipment Installation

10.4.1.1 Setup

The power measurement equipment should be installed as close as possible to the tool. Running cables long distances increases the risk of accidentally pulling the voltage and current probes off the unit being tested.

The location chosen should be close to the control monitor for the processing tool. This will allow for easy configuration and event data monitoring. Also, this facilitates the necessary time synchronization process described in the analysis section.

On most systems, it will be necessary to remove one or more of the safety shields placed in front of the breaker and contactors. Follow all local safety procedures for operating a tool without these shields in place. At a very minimum, the measurement system wiring should be routed so that the mainframe door can be closed while they are in place. This will protect against someone accidentally contacting exposed, energized surfaces.

The current transformers should be hooked up to the equipment before the potential transformers. The potential transformers are commonly large alligator-type clips that can be pulled off fairly easily if their cables are placed under stress. It is best to hook up one phase at a time, plugging each transformer (potential or current) into the meter first, then placing them in position on the tool. It is very easy to get phases crossed if several voltage or current probes are hooked to the meter simultaneously, then hooked into the device for testing.

Be careful to ensure proper orientation when placing the current transformers into operation. This will vary from manufacturer to manufacturer, but most have an arrow indicating direction of power flow. This arrow usually will need to point towards the load. If the CT is reversed, a negative power will be reported for that phase.

10.4.1.2 Configuration Check

After powering the semiconductor tool, it is best to check the initial data reported by the power meter to assure that all connections have been made properly. Depending on the reporting methods used by the meter, it is usually possible to check values in real time. Make sure that all real power reported is positive and that the phase or angles of the current and voltages are 120 degrees apart. Most loads will be lagging power factors, although it is possible to have leading power factors with switching motor and heater controllers.

Figure 3 shows an example phasor diagram with the proper orientation for voltage and current in a balanced power system. The example shows the current phasors lagging the voltage phasors by a few degrees; this indicates an inductive load.

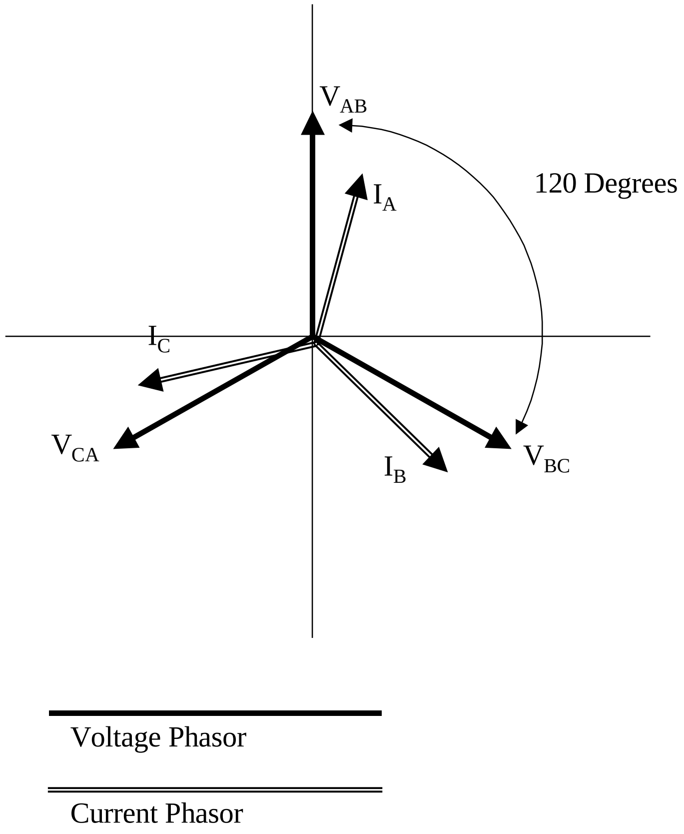


Figure 3 VI Phasor Diagram for Correct CT Installation

The length of each of the phasors indicates their magnitude. In this example, the load is perfectly balanced since they are all the same length for voltage and the same length for current. In an unbalanced system, this would not be the case.

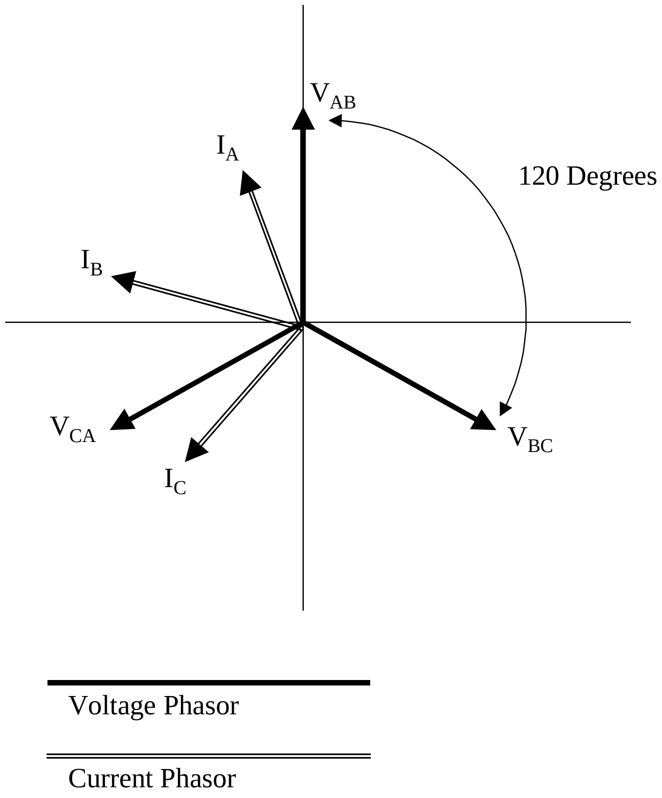


Figure 4 VI Phasor Diagram for Incorrect CT Installation

Figure 4 shows a system that has not been hooked up correctly. Notice that the I_B phasor is opposite in angle to the correct orientation. The most likely error for a problem such as this is installing the phasor B CT with the arrow facing the utility. Another way this error would be manifested is that the phase B power consumption might be reported as a negative number, indicating power being generated.

10.4.2 Necessary Process and Tool Information

10.4.2.1 Time Synchronization

To provide valid results on the energy needed for wafer processing, the data taken by the measurement system must be synchronized with the time clock on the processing tool. This eases data analysis since the event log can then be used in identifying power system events.

While performing the power audit, record the time reported by the processing tool as well as the time reported by the power measurement equipment. These two times can be used to calculate the offset between the two instruments. The offset can then be used to reference the data recorded by the power monitor to events reported in the system log.

10.4.2.2 Event Log

An event log should be created for every audit. This log should either be generated by the semiconductor processing tool or kept by hand as the operator initiates system events. The clock used should be the system time, usually displayed on the upper righthand corner of the system control screen.

10.4.2.3 Equipment Removal

10.4.2.4 CT Removal Issues

Current transformers should always be removed from the utility service before being unplugged from the metering equipment. Depending on the type and construction of the CT, damaging voltages may be induced if it is disconnected from the meter first. Check with the documentation provided by the equipment manufacturer for further information.

10.5 Analysis

10.5.1 Using Excel

Most power meters have a method of getting recorded data into a format that can be read by a personal computer with a spreadsheet program such as Microsoft Excel. Commonly these files are going to have columns of data, time-stamped and separated by commas, semicolons, or tabs. Many meters will also have custom software applications that allow the data to be looked at and analyzed off line at a desk. However, this capability falls short of performing the specialized calculations necessary for the power measurement protocol.

The data will need to be broken down into individual sections, such as the following:

- Startup
- Process
- Idle
- Shutdown

The process required to separate the sequence of data involves synchronizing the time-stamped data with events recorded in the event log of the tool or recorded by hand during the testing process. The two time clocks should be synchronized to within the recording interval of the data from the recorder. This will minimize errors in calculations resulting from time offset.

To calculate the average energy usage during wafer processing, or any other system operation period, the three-phase power consumption is needed. Next, the power consumption data during the period under examination should be averaged. Multiply this average by the total time (in hours) of the period:

$$Energy(kWH) = AveragePower(kW) \times Time(Hours)$$

To obtain the total energy required per wafer, divide this value by the total number of wafers processed during this time. Figure 5 shows a graphical example of the parsed data.

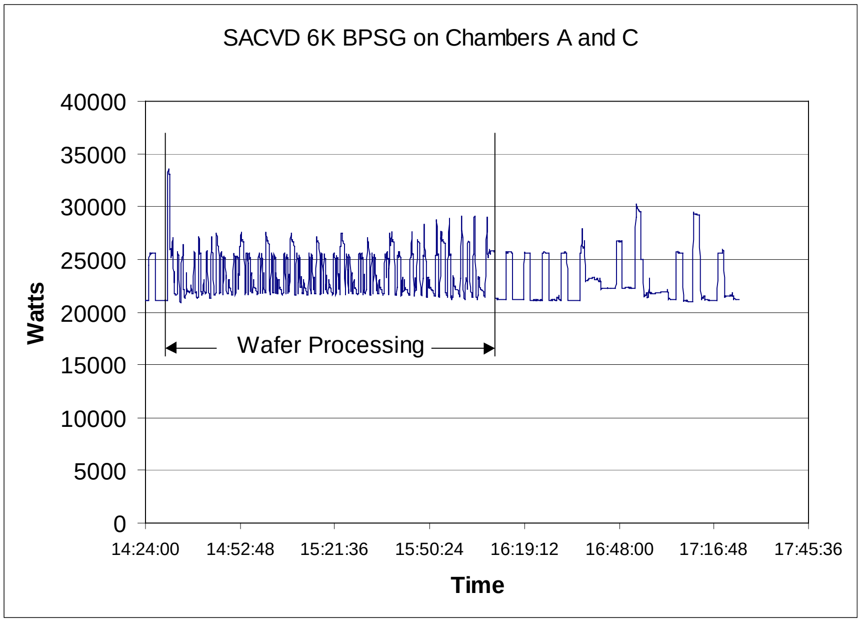


Figure 5 Power Curve Analysis Example

For complete conformance to the protocol and for a complete description of the dynamic nature of the load presented by processing tool, the average and minimum power factor during processing must be calculated. The power factor should be processed, so that only the time period under consideration is averaged. Also, the minimum power factor during this period should be reported as well.

11 FIELD GUIDANCE PROTOCOL

11.1 Purpose and Scope

The guidance document is intended as general guidance for completing an energy/power distribution audit of a semiconductor process tool. It presents guidance for electrical, exhaust, and cooling water measurements.

11.2 Electrical

11.2.1 Equipment Installation Considerations

In most cases, it is possible to install the electrical power meters without shutting down the process tool. Safely performing this requires caution and Class I electrical insulation gloves. A general inspection should be performed at the start of each audit. The inspection should include checks for the following items:

- Possible safety shield removal and safety impact
- Access to voltage test points for all measurement locations
- Access space for current transducers for all measurement locations
- Test equipment wiring issues

Depending on the location of manufacture and the manufacturer’s standards for processing equipment, voltage probe installation is often the most difficult aspect of an audit. Some manufacturers use terminal blocks that require a special voltage probe while others use buss bar schemes that are easy to access. Check before any audit by comparing the tool electrical schematics to the tool installation to find out if any difficulties will be encountered.

With an increasing number of power meters used, the amount of wiring for the testing may become difficult to manage. Every effort should be taken to maintain an orderly and neat wiring layout for all test equipment. When meters must all be installed in close proximity to each other, carefully install voltage and current probes so as not to confuse the probes between meters.

11.2.2 Current Probe Installation and Selection

Choose a current probe so that the measurement current is within 10–100% of the current rating on the probe. The flexibility of the measured conductors as well as space restrictions will often determine the choice between flexible and clamp-on probes. If there is space and the current carrying wires are stiff or are ridged buss bars, it is often best to use clamp-on probes. For crowded installations, usually only flexible current probes can be used.

11.2.3 Voltage Probe Installation and Selection

Voltage probes are usually installed after the current probes. The voltage probes will frequently be installed on buss bars or terminal strips and may not have a physically secure mounting. Any bumping or jarring from installing a current transducer may knock the voltage probes from their mounting, causing the probe to fall into the process tool—an unsafe situation. This situation should be avoided if at all possible since it creates unnecessary safety and equipment damage risks.

Figure 6 and Figure 7 show sample installations of electrical monitoring equipment.

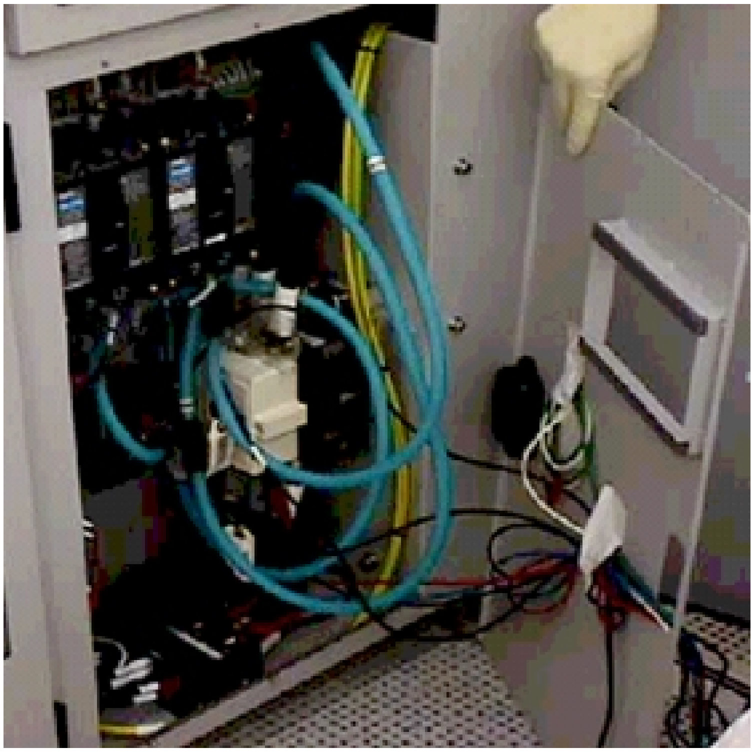


Figure 6 Typical Flexible CT Installation

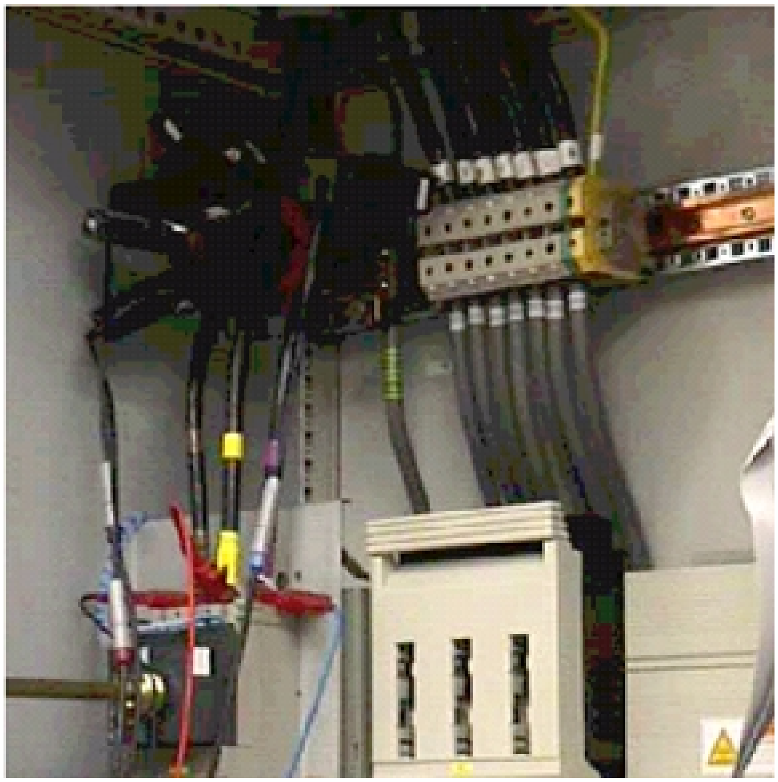


Figure 7 Typical Clamp on CT Installation

11.2.4 Safety

When possible, make all voltage and current connections without removing safety shields. This can usually be done by choosing the correct voltage probes. Often a “plunger”-style voltage probe is capable of reaching voltage test points where standard “alligator” probes cannot.

If a safety shield must be removed for test equipment installation, make sure that the shield is not interlocked. This will avoid accidentally shutting down the equipment. Removing the safety shield with the tool energized is considered “hot work.” Electrical insulating gloves should be worn for this operation. After the voltage and current probes are installed, re-install the safety panels and shields to minimize any possible safety hazards. If it is not possible to re-install the shields, place hazard cones around the area and notify all operators of the live voltage hazard. Electrical tape with a breakdown voltage higher than the exposed operating voltage of the process tool can be used to provide an extra level of **temporary** safety by reducing contact hazard. If additional safety precautions are required by local regulations, follow them as well.

11.2.5 Report Format

Table 8 shows an example report format for an electrical processing tool; the format is from the Applied Materials power measurement protocol.

Table 8 Example of Report Format Compliant with Applied Materials’ Power Measurement Protocol

Process
Duration: 3.5 hours
Wafers: 50

			Phase A	Phase B	Phase C	Total	Unit
Energy		total	13.4	12.5	14.1	40.0	kWh
		per wafer	—	—	—	0.8	kWh
		per cm^2 of silicon	—	—	—	0.0025	kWh
Power	Real	Max	49.0	88.5	35.8	27.6	kW
		Avg.	3.8	3.6	4.0	11.4	kW
	Apparent	Max.	63.3	90.1	55.3	55.4	kVa
		Avg.	11.5	11.3	11.9	34.7	kVa
	PF	Min.	0.00	0.00	0.00	0.05	—
		Avg.	0.25	0.25	0.27	0.27	—
Current	RMS	Max.	544.4	763.4	472.1	—	Amp
		Avg.	96.6	93.7	98.8	—	Amp
		Min.	0.0	3.1	0.2	—	Amp
	THD	Avg.	110.7	102.7	108.5	—	%

Relative power consumption charts should be used for reporting the usage information in a Pareto study. Table 9 shows an example of a tool chart. For this example, a two-chamber 300 mm process tool was chosen.

Table 9 Power Consumption Chart

Measurement Location	Process 1 (kW)	%	Process 2 (kW)	%	Idle (kW)	%
UPS, controller	0.65	4.4	0.65	4.4	0.65	4.7
Reactor 1 heater	1	6.7	0.9	6.1	0.9	6.5
RC1 pump	3.6	24.2	3.6	24.2	3.6	26.2
RC1 LRF	0.1	0.7	0.3	2.0	0.1	0.7
RC1 HRF	0.6	4.0	0.1	0.7	0.1	0.7
Reactor 1 misc.	0.9	6.1	1	6.7	0.9	6.5
WHC pump	0.4	2.7	0.4	2.7	0.4	2.9
IOC2 pump	0.5	3.4	0.5	3.4	0.5	3.6
IOC2 pump	0.5	3.4	0.5	3.4	0.5	3.6
Reactor 2 heater	0.9	6.1	0.6	4.0	0.9	6.5
RC2 pump	4.2	28.3	4.2	28.3	4.2	30.5
RC2 LRF	0.1	0.7	0.3	2.0	0.1	0.7
RC2 HRF	0.1	0.7	1.4	9.4	0.1	0.7
Reactor 2 misc.	0.9	6.1	1	6.7	0.9	6.5
Remote plasma clean	0.4	2.7	0	0.0	0	0.0
Clean environment	0.2	1.3	0.2	1.3	0.2	1.5
	15.05	101.3	15.65	105.4	14.05	102.2

The two chambers are different; the tool can process wafers in only a single chamber at any given time. For each component in the tool, the power consumption is evaluated for three periods: process 1, process 2, and idle. Process 1 is the process performed in chamber 1; process 2 is performed in chamber 2. *The power consumption for components associated with chamber 2 are reported at their idle power levels for the process 1 column, since chamber 2 was idle during process 1.* The inverse relationship is true for process 2.

The chart should be used to determine possible energy reduction prospects, such as large power draw for reactor 2 pumps during process in chamber 1. During this time, the power delivered to chamber 2 is necessary to just idle the chamber and should be kept to a minimum.

The electrical equipment rented for the project was calibrated on June 1, 1999. Radian-supplied equipment used for the project was calibrated on June 21, 1999.

11.3 Water Flow Measurements

An ultrasonic flow meter is the recommended velocity/flow measurement instrument for water flow measurement in semiconductor tools. Ultrasonic meters use non-intrusive technology to measure the velocity of the water in the pipe, usually in feet per second (fps or ft/s). The velocity in fps is multiplied by 60 to get the velocity in feet per minute (fpm). The inside diameter (I.D.) of the pipe is measured in inches and converted to feet. The I.D. in feet is used to calculate the area in square feet (ft^2). The velocity in fpm and area in ft^2 are multiplied together to obtain the flow rate in units of cubic feet per minute (cfm or ft^3/min). Multiplying cfm by 7.4805 gives the volumetric flow rate in gallons per minute (gpm). The example below illustrates these conversions.

Given: Average measured velocity of 5 ft/s
Pipe ID of 2 inches (2/12 = 0.17 ft)
(5 ft/s) (60 s/min) (3.14) $(0.17\text{ ft})^2$ $(7.4805\text{ gal/ft}^3)/4$ = 49 gpm

An ultrasonic flow meter specifically designed to handle the smaller pipe sizes used by cooling and ultra pure water facilities at the tool distribution level must be used for this purpose.

11.3.1 Ultrasonic Flow Meter Operation

A Parametrics model PT868 was used on the International SEMATECH Tool Energy Pareto Project. First the pipe thickness is entered into the meter or determined automatically by the meter if the optional built-in ultrasonic pipe thickness gauge is used. If the fluid is not water, a fluid-specific sound speed is entered into the meter. The meter contains a library of sound speeds for commonly used fluids; a reference book is available from Parametrics for several hundred fluids that are not already in the built-in library.

The ultrasonic flow meter uses two transducers attached to the outside of the pipe. Each transducer sends an ultrasonic signal into the moving fluid that is detected by the other transducer. The times that it takes the signals to move downstream (with the flow) and upstream (against the flow) are measured; the meter internally converts these values into fluid velocity. This is called Transit-Time ultrasonic velocity measurement.

For most semiconductor processes, Transit-Time ultrasonic technology is preferred over Doppler ultrasonic technology. Doppler devices are more commonly used for sludge applications. The Parametrics PT868 has an accuracy of 1 to 2% of the reading and a range of 0.1 to 40 fps. Parametrics reports that their instruments are compatible with all common piping materials except, possibly, Teflon.

11.3.2 Performing Water Flow Measurements

Water flow should be measured during normal tool operations (i.e., processing wafers) to determine the proper water flow rates required by the tool and to obtain accurate estimates of water stream temperature changes as a result of heat exchange with the process.

Before measuring flow, collect the following information for the liquid streams to be measured:

1. Pipe outside diameter
2. Pipe inside diameter
3. Pipe material (PVC, SS, etc.)
4. Pipe lining material (if any)
5. Pipe lining thickness (if any)
6. Fluid type

The following is a general list of guidelines that can be used with most ultrasonic flow meter systems:

1. Water velocity/flow measurements using ultrasonic flow meters should be made in a section of horizontal or upflow vertical pipe. The pipe must be full of liquid at the point of measurement. Downflow vertical pipe or non-full horizontal pipe locations are not recommended because air pockets may form, which can interfere with proper velocity/flow measurement.
2. Measure at a point that is 10 pipe diameters downstream and 5 pipe diameters upstream of the nearest flow disturbance. Flow disturbances include elbows, bends, expansions, contractions, etc. Discussions with two ultrasonic flow meter vendors (Flow Inc. and Parametrics) indicate that the absence of a measuring location meeting these industry standard criteria may introduce errors on the order of 10% or less.
3. For measurements on horizontal sections, the transducers should be mounted on the sides of the pipe, in approximately the 3 o’clock or 9 o’clock positions. This will avoid measuring around air pockets at the top of the pipe or sediment at the bottom of the pipe. The transducers should be mounted using the transducer “couplant” provided with the sensors. The “couplant” is a silicon-based gel used to help transmit the signal through the pipe wall.
4. Only pipes with skin temperatures within the transducer temperature range should be selected for measurements. Transducers are commonly rated for –40 to 300°F. It is unlikely that pipe skin temperatures outside this range will be encountered in semiconductor processes.
5. Where possible, check the ultrasonic velocity readings against a rotameter or with a bucket and stopwatch test. In most semiconductor tool installations, an inline rotameter is installed on the return line between the tool and the facility. Whenever possible, confirm that ultrasonic readings correspond with readings from the rotameter.
6. Begin measurements 5 minutes before the process step begins, collect velocity data during the entire process step, and continue measurements for 5 minutes after the process step has been completed.
7. Many ultrasonic flow meters can electronically log velocity and temperature data. It is very useful to electronically record this data. If this is not possible, a datasheet should be created to record velocity and temperature data at specific time intervals (i.e., every 5 or 10 minutes).

11.4 Water Temperature Measurements

Water temperature measurements are often performed in conjunction with water flow rate measurements so that energy balances can be performed. Water stream temperature changes are usually determined by measuring the temperature changes for cooling water between supply and return. A type K thermocouple can be used to perform the temperature measurements. A multi-channel data logger is highly recommended for simultaneously collecting multiple cooling water temperature differentials. Some ultrasonic flow meter manufacturers (including Panametrics) also offer temperature transducers as optional equipment.

Use existing thermal wells, if they are available, and insert the thermocouple as far into the well as possible. In most semiconductor tool installations, a cooling water station is installed between the tool and the facility cooling water system. The water station includes visual temperature gauges on the supply and the return. Whenever possible, confirm that local pipe wall or thermal well temperature readings correspond with those on the gauges at the water station.

If thermal wells are not available, attach the thermocouple to the outer wall of the pipe and take measures to isolate the thermocouple from temperature influences other than the outer pipe wall temperature. Nearby fans from process equipment or ambient air currents may influence the thermocouple temperature reading. Removable insulation or tape may be used to improve the accuracy of the pipe wall temperature measurement.

Be sure to use all necessary precautions and personal protective equipment (PPE) to prevent skin contact with any hot surface. There is a potential for burns when making measurements on some water lines such as a cooling water return line.

11.5 Energy Calculations for Water

Using the energy equation $Q = m\,(\text{dot})C_p\ \Delta T$

where Q = energy removed (kW)

$m(\text{dot})$ = mass flow (lb/hr)

C_p = specific heat for water (Btu/(lb-°F))

$\Delta T = T_{return} - T_{supply}$ (°F)

and $m(\text{dot}) = \delta \cdot q$

δ = density of water 8.34 1b/gal

q = flow of water in (gal/min)

then $Q = (8.34\ \text{lb/gal})(\text{gal/min})(60\text{min/hr})(1\text{Btu}/(1\text{b} - °\text{F}))(\Delta T)$

$Q = 500 \times q \times \Delta T$ (Btu/hr)

Example: $T_{supply} = 61.5$ °F

$T_{return} = 64.9$ °F

$q = 11.2$ gal/min

$Q = (500)(11.2)(3.4) = 19{,}040$ Btu/hr

or $Q = (500)(11.2)(3.4)(1\text{kW}/3412\ \text{Btu/hr}) = 5.6$ kW

11.5.1 Exhaust Flow Rate Measurement Procedure for Semiconductor Tools

11.5.1.1 Overview

Obtaining accurate and repeatable flow measurements in exhaust ducts in semiconductor facilities requires careful planning and a consistent field measurement approach. The flow rate of exhaust is usually expressed in cubic feet per minute (cfm). The flow rate in exhaust ducts is usually determined by measuring the velocity of air through the duct in feet per minute (fpm) and then multiplying the measured velocity by the area of the duct in square feet (ft^2) to get cfm.

Several documents have been published about measuring exhaust flow/air velocity. Some are written specifically for the semiconductor industry and others are for industry in general. Section A2-7 of Appendix 2 of SEMI document 2614D, *Revisions with Name Change to SEMI S2-93A, Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment*, provides guidelines for exhaust flow measurement for semiconductor tools. At the time of this writing, SEMI document 2614D (including Appendix 2) has not been formally approved, but has been approved by the voting technical committee and formal publication is expected in Q1-00. Sections 8.3.1 through 8.3.14 of SEMI S6-93, *Safety Guideline for Ventilation*, also provide guidelines for exhaust flow measurement for semiconductor tools. EPA 40 CFR Part 60, Appendix A, Method 1 Sample and Velocity Traverses for Stationary Sources and Method 1A Sample and Velocity Traverses for Stationary Sources with Small Stacks or Ducts also provide a very useful approach to accurately measure velocity in exhaust ducts.

For the International SEMATECH tool energy analysis, flow measurements were based on Section A2-7.2 of Appendix 2 of SEMI document 2614D. Section A2-7.2 calls for at least six points on each traverse on round ducts larger than 6 inches in diameter and at least 10 points on each traverse on round ducts larger than 10 inches in diameter. For very large ducts with a wide variation in velocity, Section A2-7 calls for 20 points on each traverse. No guidance is given regarding the percent of the diameter for each traverse point.

Section A2-7.3 of Appendix 2 of SEMI document 2614D provides an approach similar to EPA Method 1 for selecting the number of traverse points for rectangular ducts. Section A2-7.3 calls for at least 16 traverse points at the center of each cross section and enough points to provide less than 6-inch gaps between traverse points.

The remainder of this section summarizes EPA Method 1, an established approach that is applicable to semiconductor tools.

11.5.1.2 Components of Exhaust Flow Rate Measurement

Several factors are essential for defining an approach for measuring the exhaust flow rate in a duct:

1. Flow measurement location(s)
2. Flow measurement equipment and techniques
3. Pressure and temperature corrections
4. Checking repeatability of measurements

11.5.1.3 Duct Dimensions

The inside dimensions of the duct are used to calculate the inside area of the duct in square feet. Most often, this simply means measuring the inside diameter (I.D.) of a round duct in inches, converting to feet, and multiplying the I.D. by the following equation to calculate the inside area:

$$\text{area (ft}^2) = 3.14 \times (\text{I.D.(ft)})^2/4 \qquad \textbf{Eq. [1]}$$

For rectangular ducts, measure the inside length and width of the duct in inches, convert to feet, and multiply these two numbers to get the area in square feet.

11.5.1.4 Flow Measurement Locations

Selecting a good flow measurement location is critical in developing a plan to perform accurate velocity measurements. The goal is to select a location to measure the velocity at a point in the duct where the gas flow is uniform. Therefore, measurement locations need to be as far as possible from flow disturbances upstream and downstream of the measurement point. Examples of flow disturbances include elbows, expansions, contractions, and flow adjustment devices such as blast gates and butterfly dampers.

EPA Method 1 (§ 2.1) recommends that the flow measurement location be at least eight duct diameters downstream and at least two duct diameters upstream of the nearest disturbances.

Appendix 2 (§ A2-7.1) of SEMI document 2614D recommends that the flow measurement location be at least 7.5 duct diameters and at least three duct diameters upstream of the nearest flow disturbances. SEMI S6-93 (§ 8.3.1.1) recommends that the flow measurement location should be 7.5 duct diameters from any point of connection or fitting. It should be noted that flow measurement locations as far away from flow disturbances as specified in these documents are rarely available in a typical semiconductor facility.

In general, when the measurement location is farther away from a flow disturbance, the flow rate can be accurately measured with fewer velocity readings at that location. Conversely, more velocity measurements are required to obtain accurate and repeatable readings at a given location when that location is less than ideal with respect to flow disturbances.

As a result of friction between the exhaust gases and the duct walls, the velocity is lowest closer to the duct walls and higher toward the centerline of a straight run of circular duct. Therefore, a traverse is performed to measure velocity at different points within the duct. Another traverse, 90° offset from the first traverse, provides a complete picture of the velocity profile in the duct. Figure 8 illustrates the two traverse methods for characterizing the velocity profile in a round duct.

Figure 8 also introduces the concept of breaking the duct up into equal area sections and measuring the velocity in each section by specifying each traverse point as a percentage of the duct ID.

Traverse Point	**Distance % of diameter**
1	4.4
2	14.7
3	29.5
4	70.5
5	85.3
6	95.6

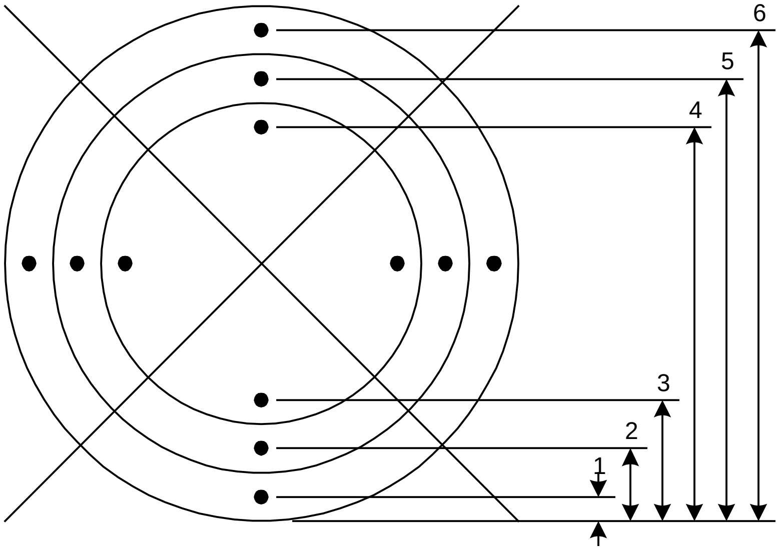


Figure 8 **Example Showing Circular Stack Cross Section Divided into 12 Equal Areas, with Location of Traverse Points Indicated**

Table 10 provides a complete listing of the traverse points as a percentage of duct ID as a function of the number of points on each traverse.

Table 10 Location of Traverse Points in Circular Stacks

	Number of traverse points on a diameter											
Traverse point number on a diameter	2	4	6	8	10	12	14	16	18	20	22	24
1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.6	1.4	1.3	1.1	1.1
2	85.4	25.0	14.6	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2
3	....	75.0	29.6	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5
4	....	93.3	70.4	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9
5	....	....	85.4	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5
6	....	....	95.6	80.8	65.8	35.6	26.9	22.0	18.8	16.5	14.6	13.2
7	....	....	....	89.5	77.4	64.4	36.8	28.3	23.6	20.4	18.0	16.1
8	....	....	....	96.8	85.4	75.0	63.4	37.5	29.6	25.0	21.8	19.4
9	....	....	....	....	91.8	82.3	73.1	62.5	38.2	30.6	28.2	23.0
10	....	....	....	....	97.4	88.2	79.9	71.7	61.8	38.8	31.5	27.2
11	....	....	....	....	....	93.3	85.4	78.0	70.4	61.2	39.3	32.3
12	....	....	....	....	....	97.9	90.1	83.1	76.4	69.4	60.7	39.8
13	....	....	....	....	....	....	94.3	87.5	81.2	75.0	68.5	60.2
14	....	....	....	....	....	....	98.2	91.5	85.4	79.6	73.8	67.7
15	....	....	....	....	....	....	....	95.1	89.1	83.5	78.2	72.8
16	....	....	....	....	....	....	....	98.4	92.5	87.1	82.0	77.0
17	....	....	....	....	....	....	....	....	95.6	90.3	85.4	80.6
18	....	....	....	....	....	....	....	....	98.6	93.3	88.4	83.9
19	....	....	....	....	....	....	....	....	....	96.1	91.3	86.8
20	....	....	....	....	....	....	....	....	....	98.7	94.0	89.5
21	....	....	....	....	....	....	....	....	....	....	96.5	92.1
22	....	....	....	....	....	....	....	....	....	....	98.9	94.5
23	....	....	....	....	....	....	....	....	....	....	....	98.8
24	....	....	....	....	....	....	....	....	....	....	....	98.9

Note: Percent of stack diameter from inside wall to traverse point.

Figure 9 illustrates the number of points required on each traverse as a function of the measurement location's distance from flow disturbances.

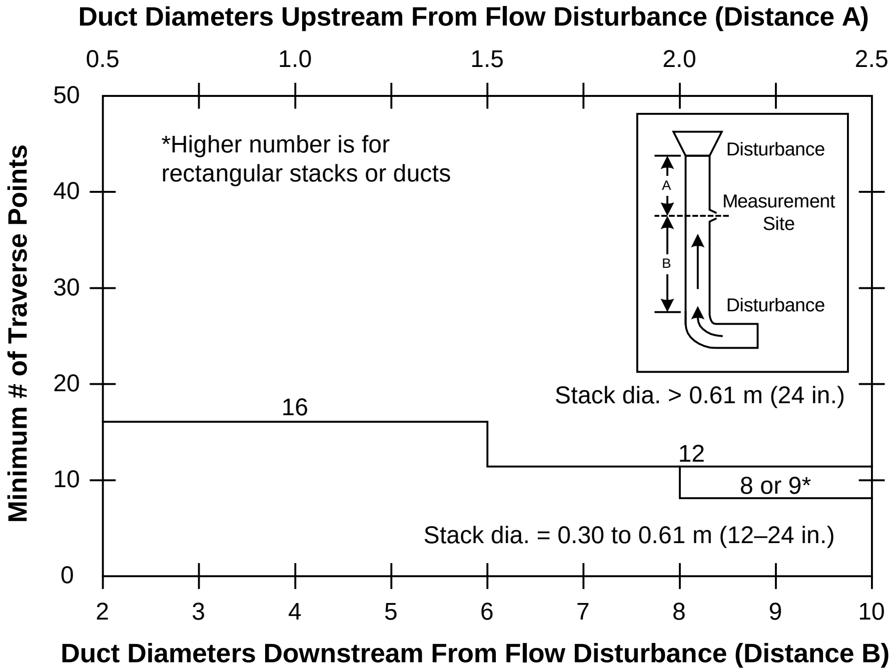


Figure 9 **Minimum Number of Traverse Points for Velocity (Non-Particulate) Traverses**

While the footnote of this table says that this table is for ducts between 12- and 24-inch diameter, EPA Method 1A (§ 1.1 and 2.2.2) also specifies the use of this table for ducts between 4 and 12 inches in diameter. Table 11 shows how the percentage of duct diameters from Figure 9 are converted into the distance of each traverse point along the traverse axis as a function of duct diameter.

Table 11 Percent of Duct Diameters Converted to Traverse Point Distances for a 16-Point Traverse

Point #	% of Diameter	4-in. Dia. Duct	6-in. Dia. Duct	8-in. Dia. Duct	10-in. Dia. Duct	12-in. Dia. Duct
1	1.6	0.06	0.10	0.13	0.16	0.19
2	4.9	0.20	0.29	0.39	0.49	0.59
3	8.5	0.34	0.51	0.68	0.85	1.02
4	12.5	0.50	0.75	1.00	1.25	1.50
5	16.9	0.68	1.01	1.35	1.69	2.03
6	22.0	0.88	1.32	1.76	2.20	2.64
7	28.3	1.13	1.70	2.26	2.83	3.40
8	37.5	1.50	2.25	3.00	3.75	4.50
9	62.5	2.50	3.75	5.00	6.25	7.50
10	71.7	2.87	4.30	5.74	7.17	8.60
11	78.0	3.12	4.68	6.24	7.80	9.36
12	83.1	3.32	4.99	6.65	8.31	9.97
13	87.5	3.50	5.25	7.00	8.75	10.50
14	91.5	3.66	5.49	7.32	9.15	10.98
15	95.1	3.80	5.71	7.61	9.51	11.41
16	98.4	3.94	5.90	7.87	9.84	11.81

Note: per EPA Method 1 Section 2.3.1.2, any points less than 0.5 inches from the wall shall be measured at 0.5 inches from the wall.

There is an important note regarding traverse points close to the duct walls. For ducts with a diameter of 24 inches or less, all calculated traverse points less than 1/2 inch from the duct wall are replaced with a single measurement point 1/2 inch from the wall. Refer to EPA Method 1 §2.3.1 for more discussion on this topic and for similar criteria for ducts with a diameter greater than 24 inches.

Table 12 is an example of a field datasheet. This field datasheet provides a place to record the velocity at each traverse point as well as other critical variables such as exhaust temperature and pressure.

After the velocity at each traverse point is measured and recorded, the average velocity is found by taking the average of the traverse point velocities.

Table 12 Field Data Sheet

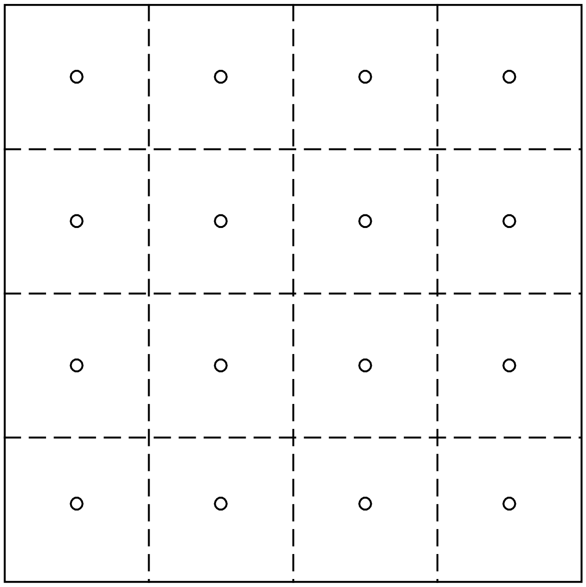
FIELD DATA SHEET - SEMATECH PROJECT ESHD007

Datasheet Number	1				
Facility					
Date					
Time					
Source (Gas Cabinet, Wet Bench)	Wet Bench				
Sample Location (Acid Exhaust, Heat Exh.)	Corrosive Exhaust				
Operating Mode (Processing, Idle, Clean)	Idle				
Sampler 1 Name	RWM				
Sampler 2 Name	CTL				
Ambient Pressure (in Hg)	25.5				
Ambient Temperature (°F)	70				
Static Pressure (in H_2O vacuum)	-1.5				
Exhaust Gas Temperature (°F)	73				
Diameter (inches at pt. of measurement)	10				
Sample Port Diameter (inches)	0.5				
Sample Port Depth (inches)	0				
Distance Upstream (inches)	53				
Distance Downstream (inches)	28				
Field Observations:					
	Traverse Point	Temp (°F)	Velocity (ft/min)	Temp (°F)	Velocity (ft/min)
	1	—	—	—	—
	2	72.5	1197	73.1	778
	3	72.5	773	73.1	983
	4	72.5	993	73.1	1175
	5	72.5	882	73.1	1177
	6	72.5	1075	73.1	1207
	7	72.5	1199	73.1	1161
	8	72.5	1199	73.1	1128
	9	72.5	1127	73.1	1109
	10	72.5	1107	73.1	1146
	11	72.5	1147	73.1	1109
	12	72.5	961	73.1	1106
	13	72.5	1030	73.1	1060
	14	72.5	930	73.1	946
	15	72.5	686	73.1	910
	16	—	—	—	—
Average Velocity (ft/min)	1046				
Average Flow (actual ft^3/min)	571				
Average Flow (standard ft^3/min)	484				

A similar process is followed for rectangular ducts. Table 13 and Figure 10, used in conjunction with Figure 9, illustrate the traverse point number selection and location process for rectangular ducts.

Table 13 Cross-Section Layout for Rectangular Stacks

Number of Traverse Points	Matrix Layout
9...	3 × 3
12...	4 × 3
16...	4 × 4
20...	5 × 4
25...	5 × 5
30...	6 × 5
36...	6 × 6
42...	7 × 6
49...	7 × 7



Note: Example showing rectangular stack cross section divided into 12 equal areas, with a traverse point at centroid of each area.

Figure 10 Rectangular Stack Cross Section

11.5.1.5 Flow Measurement Equipment and Techniques

The two most commonly used velocity measurement devices in semiconductor facilities are the Shortridge electronic micromanometer and the hot wire anemometer. Other devices such as pitot tube/manometer combinations may also be used.

The Shortridge measures total pressure (velocity pressure plus static pressure) and static pressure using a pitot tube connected to the electronic micromanometer. It also measures temperature and barometric pressure. It can also be used to measure the differential pressure between two points, which is often useful in exhaust balancing projects. The Shortridge is pre-programmed to compute the velocity pressure and report corresponding velocity of air.

The Shortridge is capable of measuring velocities of 25 to 30,000 fpm. Accuracy is ±3% of reading ±5 fpm for velocities of 25 to 10,000 fpm. For instance, if you measure 1,000 fpm with a calibrated Shortridge, the actual velocity will be between 965 and 1,035 fpm. Shortridge does not certify accuracy above 10,000 fpm, but velocities in this range are not expected in semiconductor exhaust duct systems. The measuring temperature range of the Shortridge is –65°F to 250°F. Accuracy is ±1.0°F from -65°F to 32°F, ±0.5°F from 32°F to 180°F, and ±1.0°F from 180°F to 250°F.

An important feature incorporated into the Shortridge instruments is the ability to measure actual velocity based on local temperature and pressure conditions. Temperature and pressure affect the density of air. Plugging the temperature sensor into the Shortridge during measurements tells the instrument to measure actual temperature and barometric pressure conditions and report velocity in actual fpm (afpm) based on local temperature and pressure conditions.

Most hot wire anemometers do not account for local exhaust temperature and pressure conditions. Hot wire anemometers report standard fpm (sfpm) at 29.92 inHg and 70°F. Use the following equation to convert hot wire anemometer measurements in sfpm to afpm for comparison with Shortridge measurements in afpm:

$$\text{afpm} = \text{sfpm} \times (29.92/P_b) \times ((460 + T)/530) \qquad \textbf{Eq. [2]}$$

where P_b is the barometric pressure in inHg and T is the exhaust gas temperature in °F.

Hot wire anemometers are also commonly used to measure air flow in the semiconductor industry. Some types also measure airflow temperature. Hot wire anemometers actually measure the mass flow rate of gas passing over a heated wire. The wire is called a thermistor. The wire is heated to a certain temperature and the power required to keep the wire at that temperature is measured. The power required to keep the wire at the target temperature is referenced to a given velocity of air passing by the wire. The cooling of the wire (and therefore, the power required to heat it back up) actually depends on the mass of air passing over the wire. The relationship of air mass and air velocity is based on standard conditions (normally 29.92 inHg and 70°F). Therefore, most anemometers report velocity in sfpm at 29.92 inHg and 70°F. If the measurement location is at an altitude significantly different from sea level or exhaust duct gas temperatures are not close to 70°F, the actual velocity in afpm will differ from what was indicated in sfpm by the anemometer. Converting between afpm and sfpm is discussed in greater detail below.

The velocity measured with a hot wire anemometer in an exhaust duct can fluctuate. For the Tool Energy Analysis Project, the anemometer gathered data for approximately 15 seconds at each traverse point and recorded the average velocity. Most anemometers will automatically calculate and report the minimum, maximum, and average velocity. An Alnor CompuFlow Model 8575 anemometer was used at the first member company site. The accuracy for this instrument is ±2% of the reading ±20 fpm. For instance, 1,000 fpm is measured with a calibrated Alnor Model 8575 anemometer, the actual velocity is between 950 and 1,050 fpm. Other hot wire anemometer manufacturers report similar accuracies. The Alnor hot wire anemometer was calibrated on May 21, 1999, by the supplier.

11.5.1.6 Pressure and Temperature Corrections

If the velocity measurement device such as a hot wire anemometer does not automatically correct for local temperature and barometric pressure, corrections must be made for the difference in actual velocity relative to velocity at standard conditions (usually 29.92 inHg and 70°F). See Eq. [2] for more details.

Use the following equation to correct velocity for temperature differences from standard temperature:

$$\text{afpm} = \text{sfpm} \times ((460 + T)/530) \qquad \textbf{Eq. [3]}$$

where T is the exhaust gas temperature in °F.

Use the following equation to correct velocity for pressure differences from standard pressure:

$$\text{afpm} = \text{sfpm} \times (29.92/\text{Pb}) \qquad \textbf{Eq. [4]}$$

where P_b is the local barometric pressure in inHg.

Since flow rate is the product of velocity times a constant area, all of the equations in Sections 2.3 and 2.4 can be used interchangeably for velocity and flow rate (sfpm replaced by scfm and afpm replaced by acfm).

Section 8.3.4.2 of SEMI S6-93 also provides a good summary of the approach for making corrections for actual temperature and pressure conditions.

It is important to understand the type of reading that the velocity measurement device will provide (standard or actual condition basis) and to collect any other data necessary (exhaust gas temperature and local barometric pressure) to convert velocity and flow rate data to actual conditions.

11.6 Energy Calculations for Air

Assume exhaust constituents are mostly air.

Using the energy equation Q = m (dot) Cp ΔT

where Q = energy removed (kW)
m(dot) = mass flow (lbm/hr)
C_p = specific heat for standard air (Btu/(1b°F))
$\Delta T = T_{duct} - T_{ambient}$ (°F)

and m(dot) = $\delta \cdot q$
δ_{air} = density of air (0.075 lbm/ft^3)
q = flow of air (ft^3/min)

then $Q = (0.075 \text{ lbm/ft}^3)\ q\ (\text{ft}^3/\text{min})\ (60\text{min}/1\text{hr})\ (0.24 \text{ lbm}/(1\text{b}–°\text{F}))\Delta T$

$Q = 1.08 \times q \times \Delta T$ (Btu/hr)

Example: T_{duct} = 80 °F q = 200 cfm
T_{amb} = 70 °F
Q = 1.08 x 200 (80 –70) = 2160 Btu/hr
or Q = (1.08)(200)(10)(1 kW/3412 Btu/hr) = 0.6 kW

APPENDIX A
SAFETY

Normal electrical safety procedures as specified by the National Fire Protection Association (NFPA) 70E *Standard for Electrical Safety Requirements for Employee Workplaces*, as well as local safety regulations that might apply, should be followed.

If possible, the equipment should be de-energized before hooking up any power meter for measurements. In some cases, the tool owners may not allow a complete tool shutdown. Proper safety procedures should be followed for making live measurements.

Employees without electrical safety training (unqualified persons) should never cross the restricted approach boundary while working on energized equipment. According to the NFPA 70E standard, for systems less than 300V, unqualified and qualified employees should avoid contact. For systems between 300V and 750V, the minimum approach distance for an unqualified person is 12 inches. For systems with distribution voltages of 300V or greater, a qualified employee is needed to make connections to energized equipment.

While connecting power meter probes on equipment with distribution voltages less than 300V, both qualified and unqualified employees must wear the proper safety equipment. At a very minimum, this equipment should consist of insulating gloves rated for protection against the highest expected system voltage and safety glasses. Other equipment may be necessary as specified by local company procedures.

All conductive articles worn should be removed or insulated. This includes jewelry, watch bands, bracelets, key chains, or unrestrained metal frame glasses.

When working in a restricted space with energized equipment, precautions must be made so that equipment does not make accidental contact with exposed conductors. This includes tools, access panels, rack doors, and all conductive equipment. In addition, all access doors should be secured to prevent them from swinging into and knocking an employee into an energized circuit.

The power meter should be located far enough away from the operating circuit in a safe location so that it can be monitored during testing. Precautions should be made to prevent accidental removal—from tripping on or catching wires with equipment—of the voltage and current leads attached to the equipment and power meter. The leads should be connected, paying careful attention to any safety hazards caused by their presence in the energized equipment.

APPENDIX B
CONFIGURATION DATA

1	Main Frame Product Name	
2	Tool Type	
3	Date	
4	Location	
5	Model and Serial Number of System	
6	Wafer Size	
7	Number of Chambers if Multi-chamber tool	
8	Type of Chambers	
9	Environment Chamber	
10	Furnace Type and Capacity	
11	Number of Tracks	
12	Pump Type and Size	
13	Water Heater	
14	Other Notations	

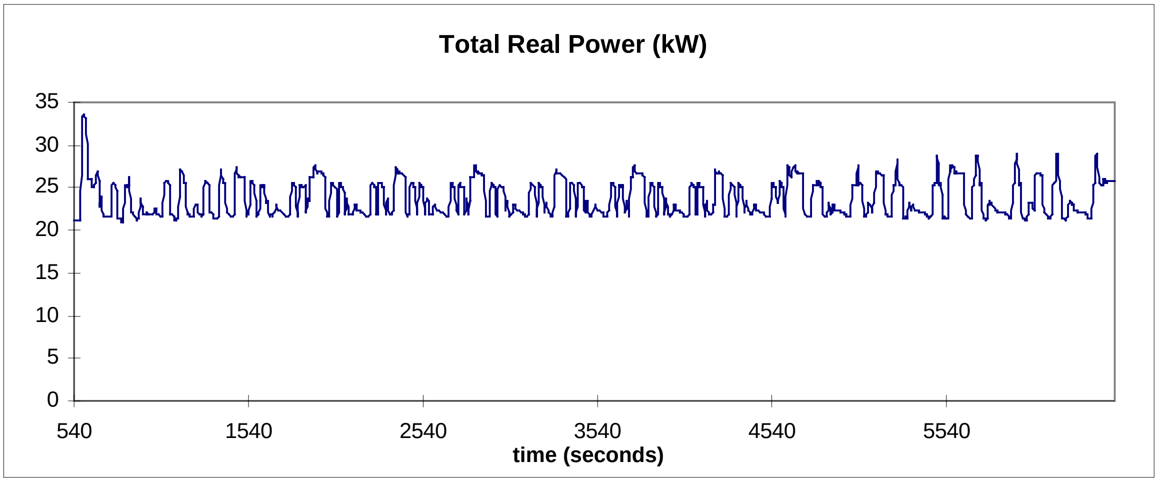
APPENDIX C
PROCESS DESCRIPTION DATA

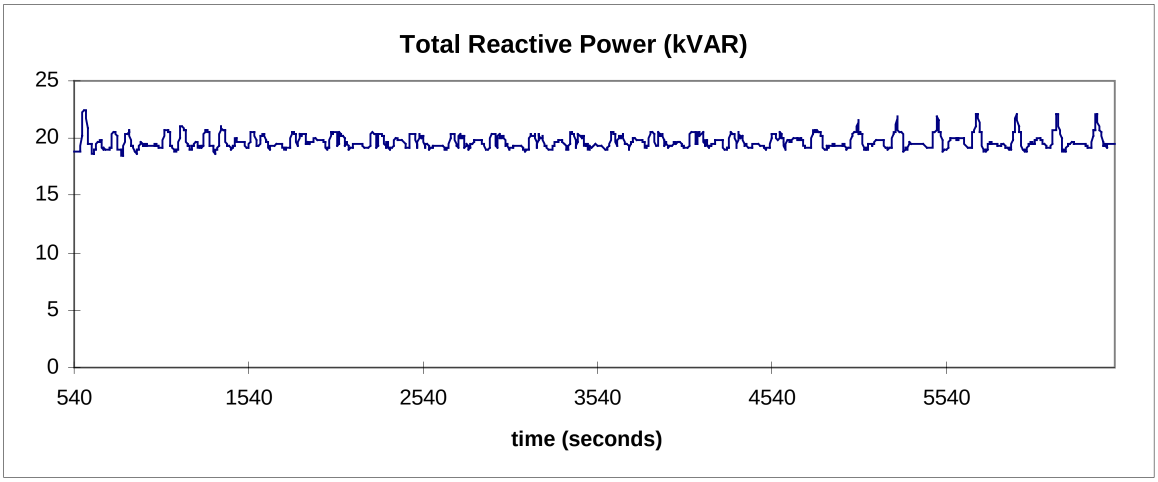
Number	Category	Entry
1	Main Frame Product Name	
2	Tool Type	
3	Date	
4	Location	
5	Wafer Handling Sequence	
6	Chamber Temperature	
7	Gas Mixture	
8	Flow Rates	
9	Pressure	
10	Process Name	
11	Physical Description	

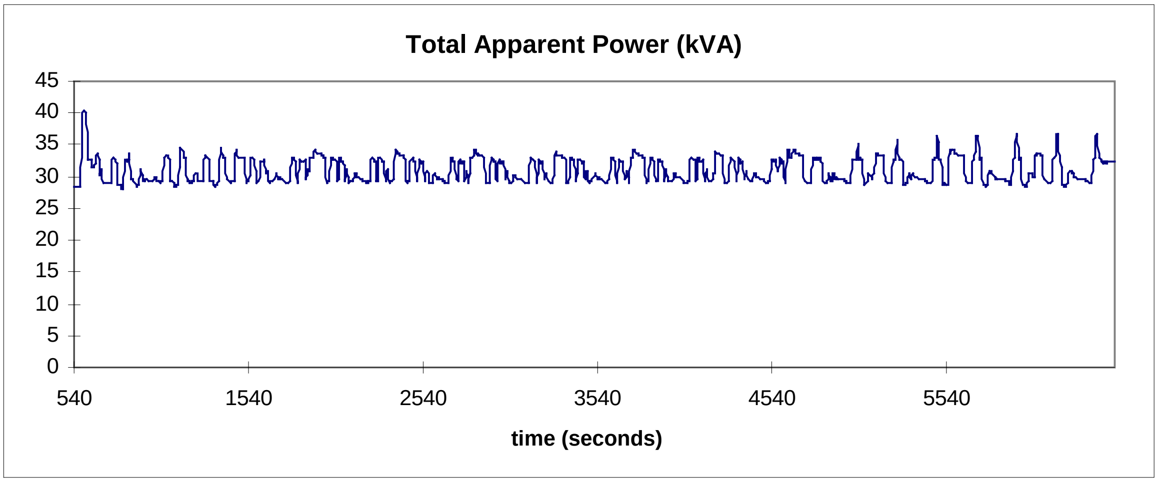
APPENDIX D
SAMPLE REPORT

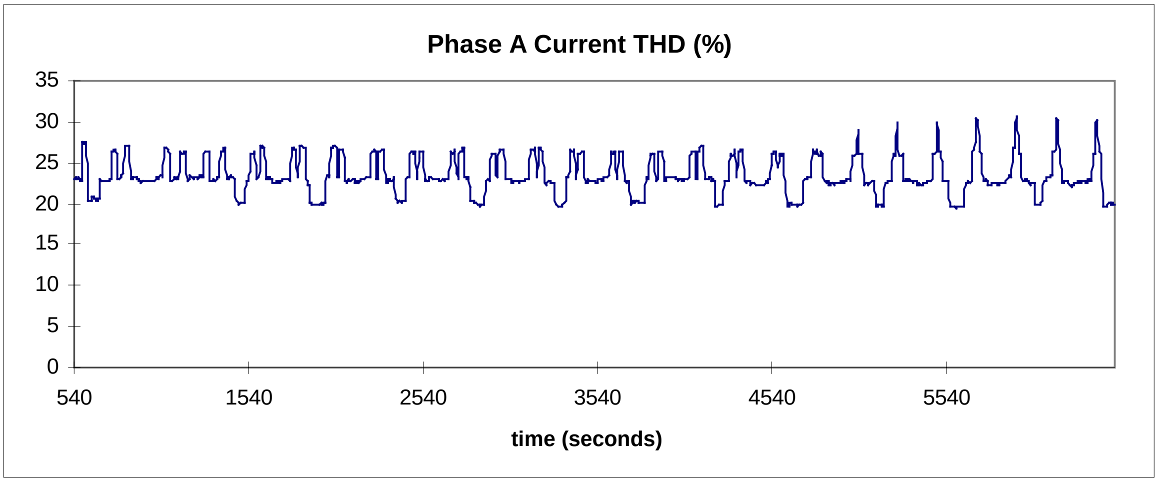
Process 6000A Deposition
Duration: 0.6 hours
Wafers: 25

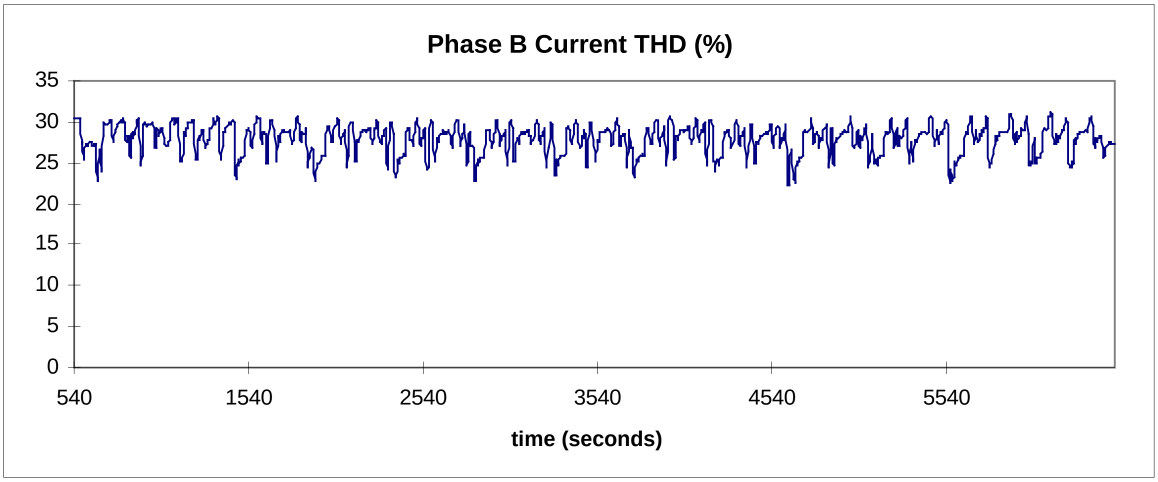
			Phase			
		A	**B**	**C**	**Total**	**Unit**
Energy						
	Total	3.3	4.8	3.1	11.2	kWh
	Per Wafer	–	–	–	0.4	kWh/Wafer
Power						
	Real					
	Maximum	6.8	9.3	6.1	21.5	kW
	Average	5.2	7.4	4.7	17.3	kW
	Aparent					
	Maximum	7.8	5.9	4.4	17.4	kVA
	Average	6.8	5.2	4.1	16.2	kVA
	PF					
	Maximum	0.50	0.72	0.70	0.66	–
	Average	0.60	0.81	0.75	0.72	Lagging
Current						
	RMS					
	Maximum	83.7	88.1	61.2	–	Amp
	Average	70.3	73.9	51.5	–	Amp
	Minimum	58.2	63.5	45.6	–	Amp
	THD					
	Average	10.8	15.5	15.4	–	%

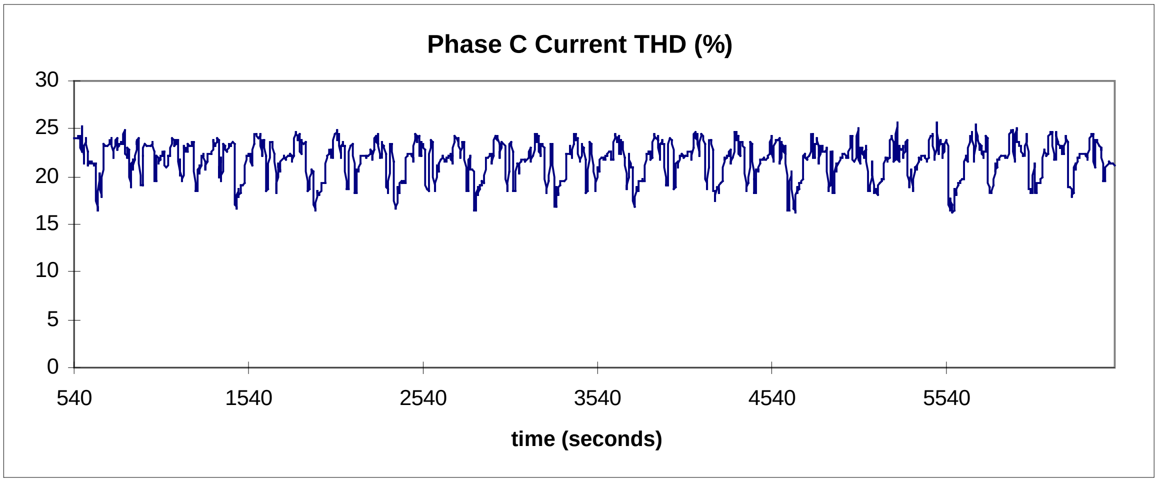

Total Real Power (kW)
35
30
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)


Total Reactive Power (kVAR)
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)


Total Apparent Power (kVA)
45
40
35
30
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)


Phase A Current THD (%)
35
30
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)


Phase B Current THD (%)
35
30
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)


Phase C Current THD (%)
30
25
20
15
10
5
0
540
1540
2540
3540
4540
5540
time (seconds)

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