Development of Parametric Inventories for Semiconductor Wafer Fabrication

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing TeleSeminar

May 27, 2004

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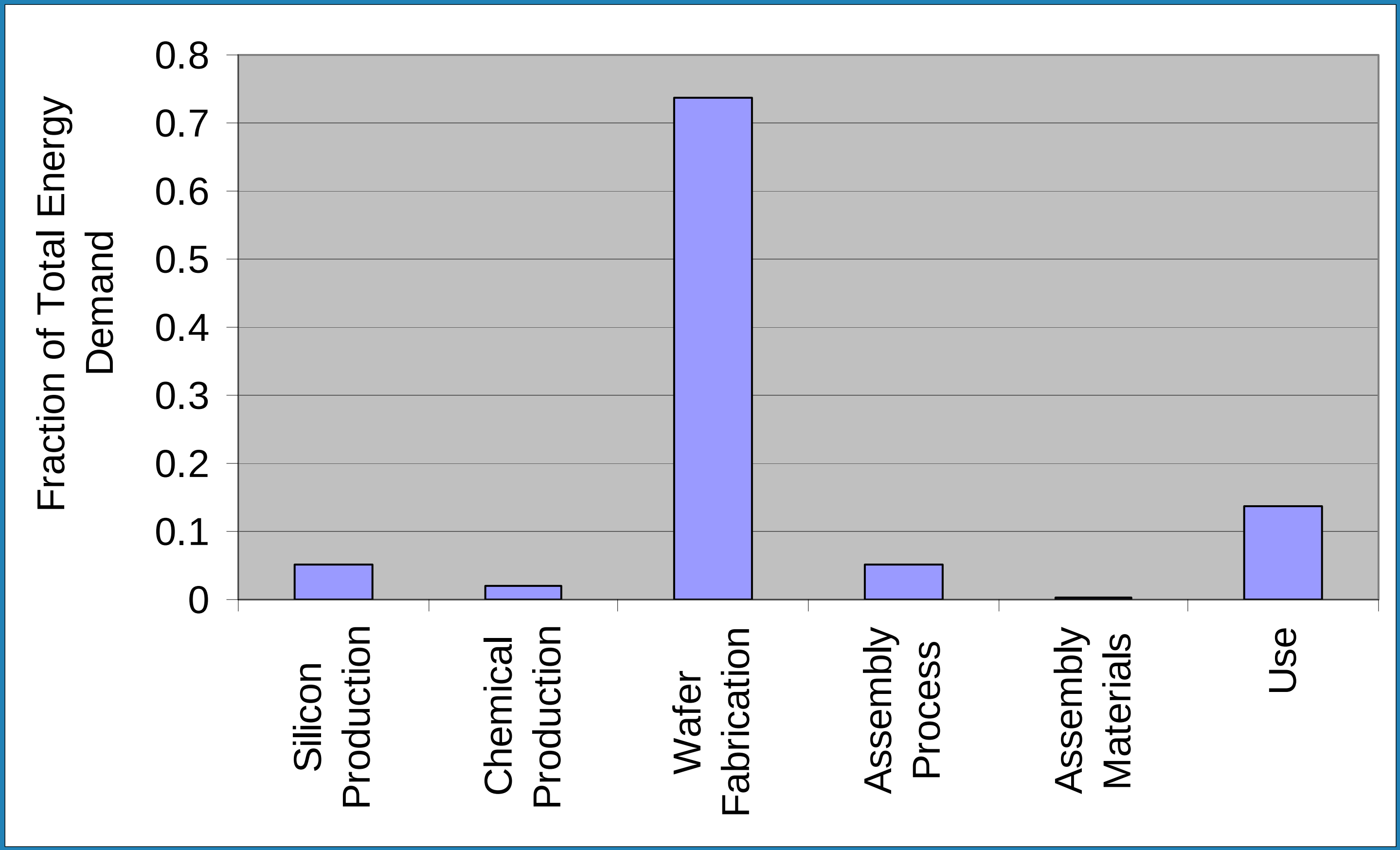
Why Life Cycle Inventory

- Focus is often on the “impact” portion of Life Cycle Analysis (LCA)
- BUT impact is not valid if inventory is not valid (or nonexistent).
- For most products, inventories can be developed by
  - Reverse engineering of products and/or
  - Analyzing relatively simple processes

Energy Requirements for Use and Manufacture of a Microchip



Adopted from Williams, et al (2002) with modifications based on SEMATECH survey

Focus on Wafer Fab

- Exact numbers may not be available, but all available data suggest that wafer fab is most critical phase for energy
- Assumptions:
  - Energy consumption is reasonable surrogate for mass balances
  - Energy is critical for multiple impacts (resource consumption, global warming, etc)

Developing Life Cycle Inventories for Wafer Fabrication

- Wafer fabrication is resource intensive, using large amounts of energy, water, and chemicals
- Inventories are poorly understood or documented
- Reverse engineering of the silicon chip reveals little about how it was manufactured
  - Most of the materials used in the manufacturing process never reside on the wafer or are later removed
- Process flows (the sequence of unit operations and recipes) are complex and change rapidly

Challenges for Resource Inventory Development in Wafer Fab

- Many products, each with short life-times (18 to 24 months)
- Product-based approach requires frequent development of many inventories (one per product)
- Difficult to predict how changes in product or process design (including equipment selection) will affect inventory
- Difficult to perform tradeoff analyses

Alternative Approach

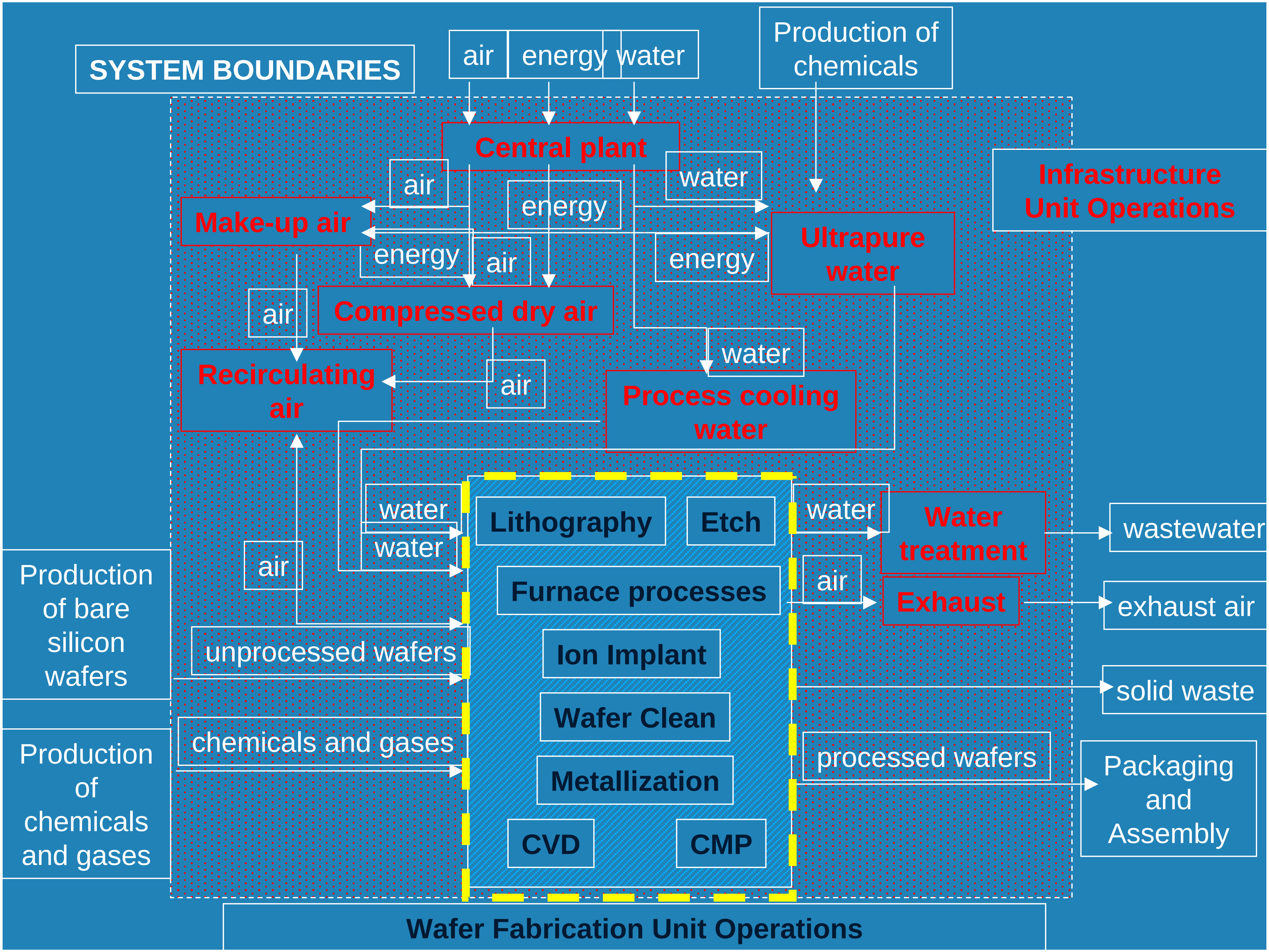
- Get 80% of the information with 20% of the data
- Develop process-based, parametric modules where material and energy flows are related to
  - Equipment type (technology)
  - Material selection
  - Product design
- Develop “typical” mass and energy flows for each unit operation, with the opportunity to add detail as needed

Requirements

- Define system boundaries
- Define functional unit
- Define inventory focus
- Define system of data organization and management

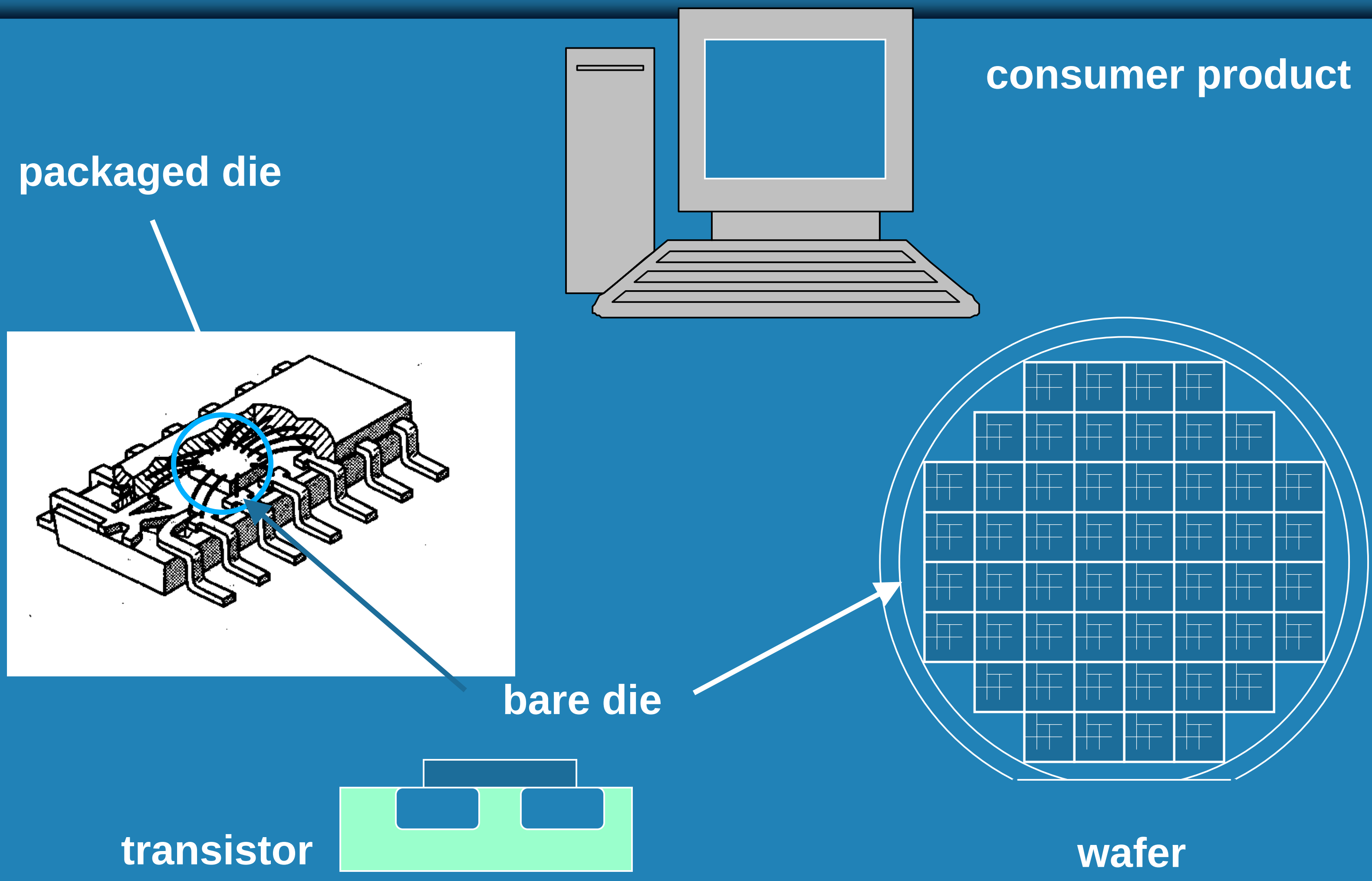
System Boundaries

- Gate-to-gate approach suitable for later insertion into full LCA
- To date, have looked only at direct wafer fabrication processes, but hope to include infrastructure as well



SYSTEM BOUNDARIES
air
energy
water
Production of chemicals
Central plant
air
energy
water
Make-up air
energy
air
energy
Ultrapure water
Infrastructure Unit Operations
air
Compressed dry air
water
Recirculating air
air
Process cooling water
water
water
air
Lithography
Etch
Furnace processes
Ion Implant
Wafer Clean
Metallization
CVD
CMP
water
Water treatment
air
Exhaust
wastewater
exhaust air
solid waste
Production of bare silicon wafers
unprocessed wafers
Production of chemicals and gases
chemicals and gases
processed wafers
Packaging and Assembly
Wafer Fabrication Unit Operations

Possible Functional Units



Functional Unit Selection

- Consumer product (e.g., computer)
- Packaged component
- 1 cm^2 of processed silicon ("die equivalent")
- Fully processed wafer

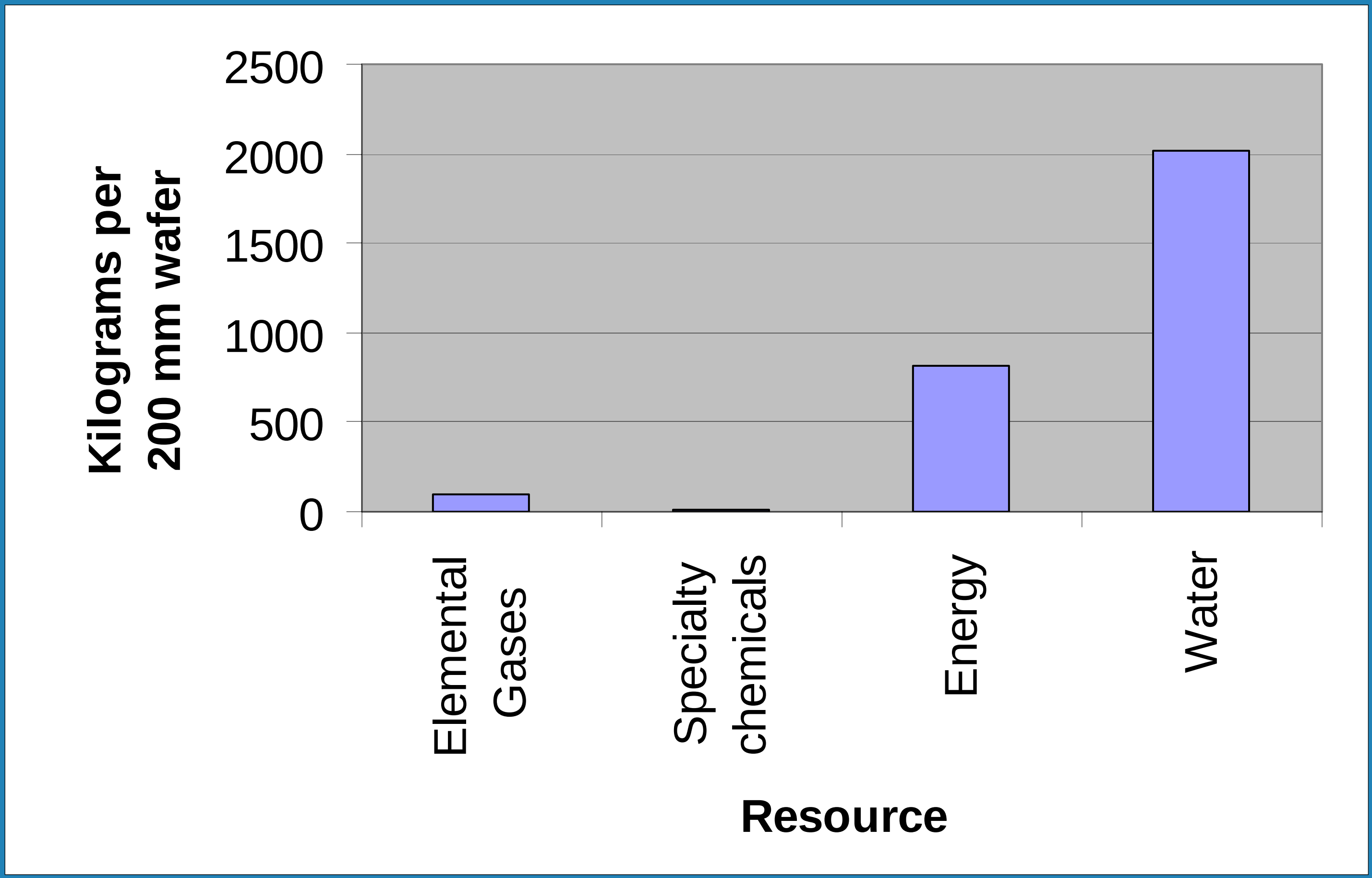
Functional Unit: Wafer

- Focus is at the level where most of the material and energy flows occur
- Good sensitivity to both process and product variations
- Data is more "generic" or universally applicable when managed at the wafer level than at the die level
- Only 3 different wafer sizes for CMOS. Increase in wafer size only slightly increases material and energy flows
  - e.g. 400 kWh per 4 inch wafer with 52 1 cm2 die per wafer and 500 kWh per 8 inch wafer with 261 die per wafer – only a 20% error if use wafer data, but 500% error if use die

Top "20" Chemicals of Interest

- Sulfuric Acid (H_2SO_4)
- Isopropyl Alcohol ($(CH_3)_2CHOH$)
- Phosphoric Acid (H_3PO_4)
- Hydrochloric Acid (HCl)
- Tetramethyl Ammonium Hydroxide ($(CH_3)_4NH_4$)
- Nitric Acid (HNO_3)
- Hydrofluoric Acid (HF)
- Hydrogen Peroxide (H_2O_2)
- N-Methyl Pyrrolidone (C_5H_9NO)
- Nitrogen Trifluoride (NF_3)
- Ammonium Fluoride (NH_4F)
- Ammonium Hydroxide (NH_4OH)
- Butylacetate ($CH_3COO(CH_2)_3CH_3$)
- Ethyl Lactate ($C_5H_{10}O_3$)
- Hexamethyl Disilazane ($C_6H_{19}NSi_2$)
- Silica, Amorphous (SiO_2)
- Sodium Hydroxide (NaOH)
- Propylene Glycol Monomethyl Ether Acetate ($C_6H_{12}O_3/CH_3CH(OCOCH_3)CH_2OCH_3$)
- Acetic Acid (CH_3COOH)
- Water
- Photo Resists
- Energy
- ACT-690c ($H_2N(CH_2)_2OH$)
- Acetone (CH_3COCH_3)

Resource Consumption in the Wafer Fab



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Inventory Focus

- Specialty chemicals are small portion of inventory
  - Costly on a per unit basis (e.g. $500/liter of resist)
  - Tied to specific processes (photolithography), thus mass balances are straightforward
  - Environmental impacts are relatively easy to define (MSDS)
- Energy, water, and elemental gases form the bulk of the inventory
  - Important - economically and environmentally
  - Much less sensitivity to proprietary data
  - More challenging to accurately measure because ubiquitous (not tied to specific process)

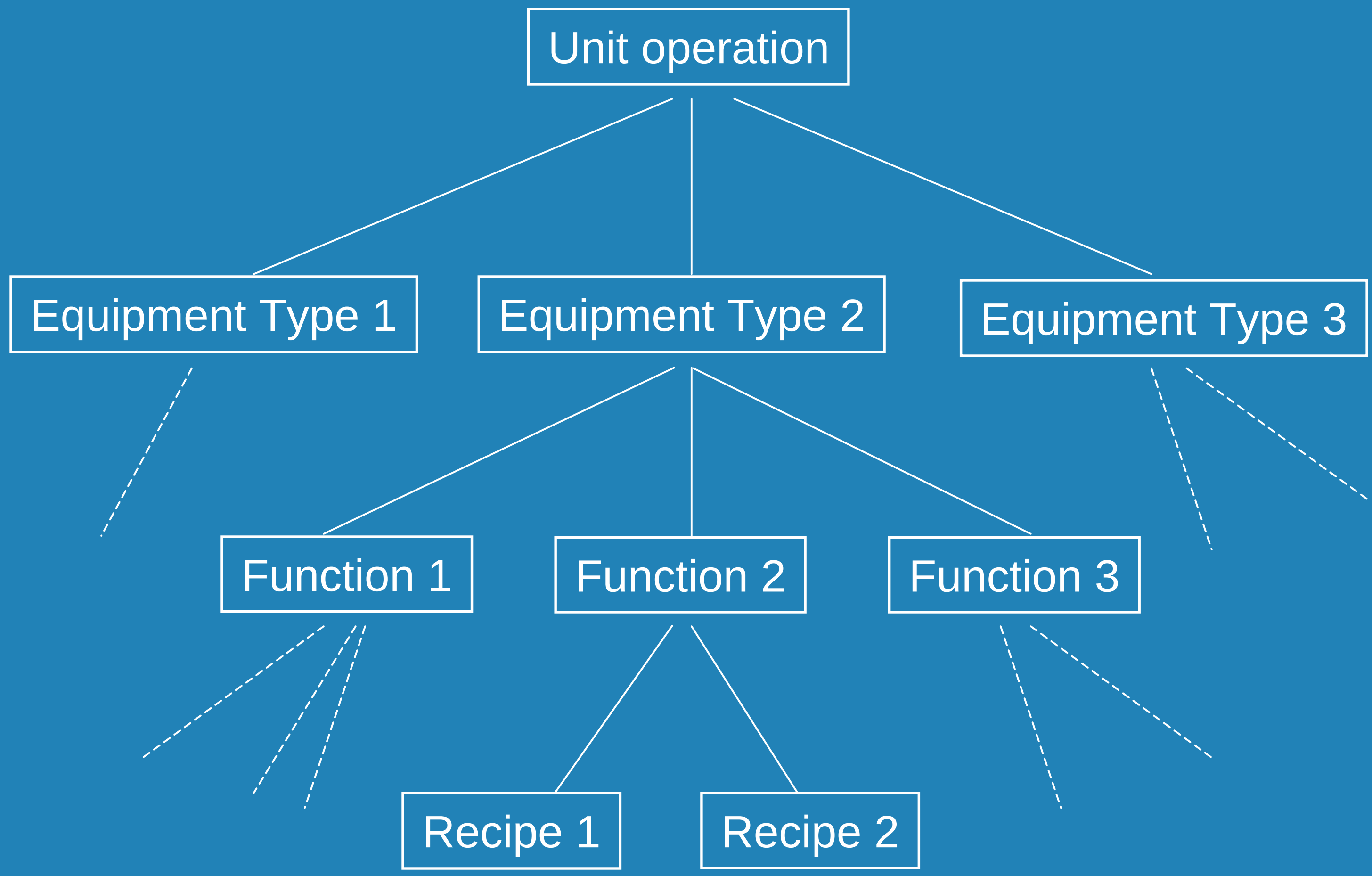
Cost of Energy vs. Photoresist

- Wafer with 20 mask layers, resist at $500/liter, and 3 ml of resist per layer = $30 per wafer
- Wafer that requires 500 kWh per wafer at $0.06 per kWh = $30 per wafer

Unit Operations as Focal Point for Inventory Development

- Unit operations relatively unchanged for the last 45 years
- Relatively little variation between fabs (due to equipment cost)
- Most variation in resource inventory can be approximated based on equipment type and process recipes

Parametric Module Levels



Wafer Clean and Furnace Unit Operations

- Significant use of energy, water, and elemental gases
- Reasonably uniform from facility to facility
- Large body of general knowledge (less proprietary than other operations)
- Relatively easy to differentiate between equipment types (e.g. horizontal vs. vertical furnaces) and processes (e.g. KOH and RCA)

Material and Energy Consumption

- Use mixture of
  - Process (equipment) recipes
  - Direct monitoring of equipment
  - Mass and energy balances at unit operation
- Treat as a “cost of ownership” problem; look at consumption for
  - Production
  - Test wafers
  - Idle time
  - Maintenance

Material Consumption – Use of Process Recipes

- Consumption of chemical A for recipe with n steps

$$Consumption_A = \sum_{1}^{n} time(i) \times flow_A(i)$$

- Assumptions
  - Design flow is attained instantaneously in the system
  - No transition state
- Verified with MFC data when available

Energy Consumption

- Furnaces
  - Equipment monitoring data
  - Direct measurement (generally not practical)
- Wet Cleans

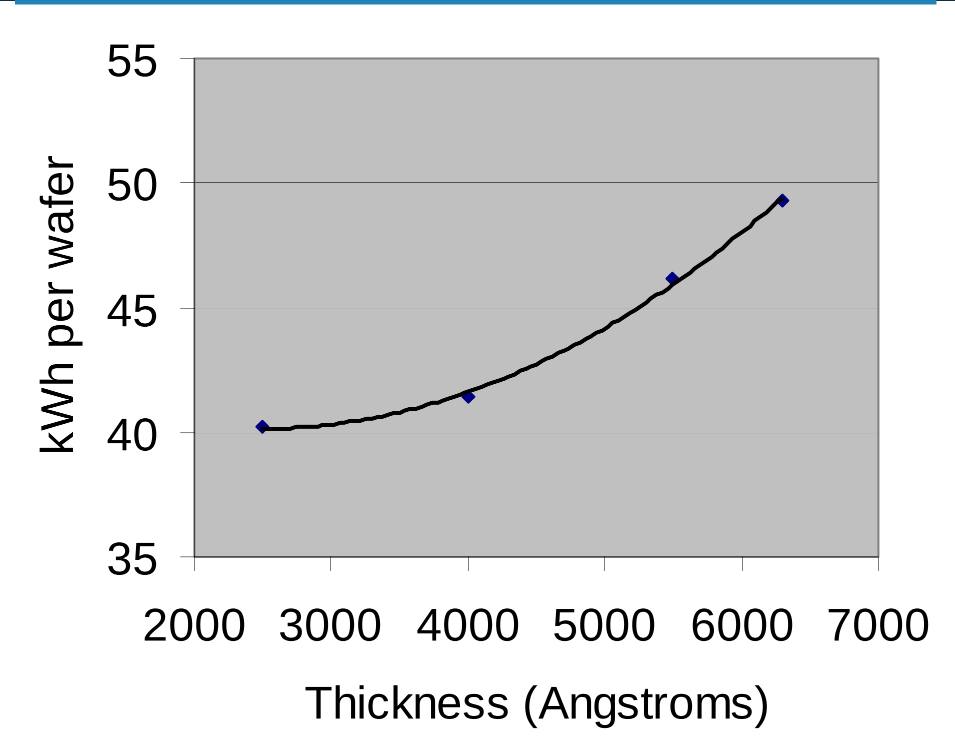
$$P_{heating} = \frac{V \times \rho \times c_p \times \Delta T}{\eta}$$

  - Use physical and chemical data from MSDS where available
  - Assume efficiency factor of 80% (i.e., 20% lost to atmosphere)

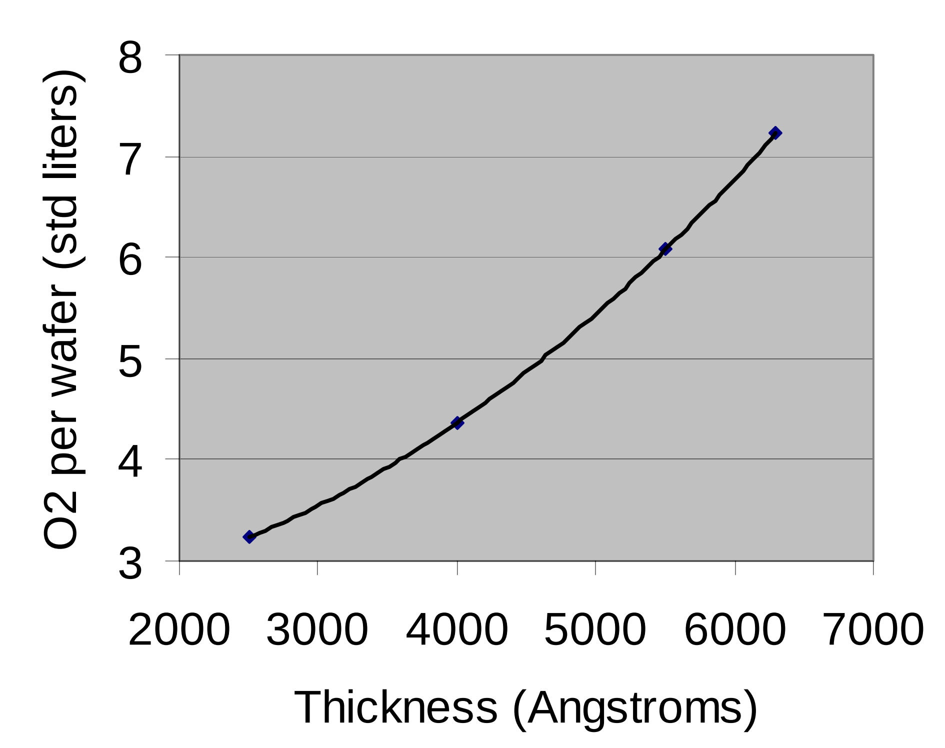
Example of Module at Function Level: Thermal Oxide

Energy and Oxygen Consumption as Functions of Film Thickness

Energy Consumption



Oxygen Consumption



Example of Module at Equipment Level

- Wafer Clean Operation
  - Different equipment types
  - Same function (standard clean)
  - Same chemistries
- Analysis includes idle time and test runs as well as actual processing

Wet Bench vs. Spray Clean – SPM/HF/RCA

Material	Wet Bench cc per wafer	Spray Cleaning cc per wafer
49% HF	6.0	2.6
$H_2SO_{4,}$	110.3	71.2
HCl	23.0	20.2
H_20_2	56.5	94.8
NH_4OH	16.1	21.7
DI	21,391	37,754
IPA	324.8	0
N_2	No data	1,017,554

Scenario 1

- A facility uses 10 SPM/HF/RCA cleans per wafer (averaged for all products) and wants to switch from wet bench to spray cleaning process
- Question – What is the effect on DI water consumption?
- Answer – increase of 16 liters per wafer

Examples of Modules at the Unit Operation Level :

- Consider both equipment selection and throughput
- Vertical furnace (batch process) vs. Rapid Thermal Process (RTP) (single wafer)
- Results may vary by facility or even within a facility

Vertical Furnace vs. RTP

- Direct measurements
  - RTP
    - 48 kW production
    - 45 kW idle
  - Vertical
    - 21 kW production
    - 16 kW idle
- Assumptions
  - Equipment is operating 131 hours per week (80% of 168)
  - Vertical furnace is fully loaded

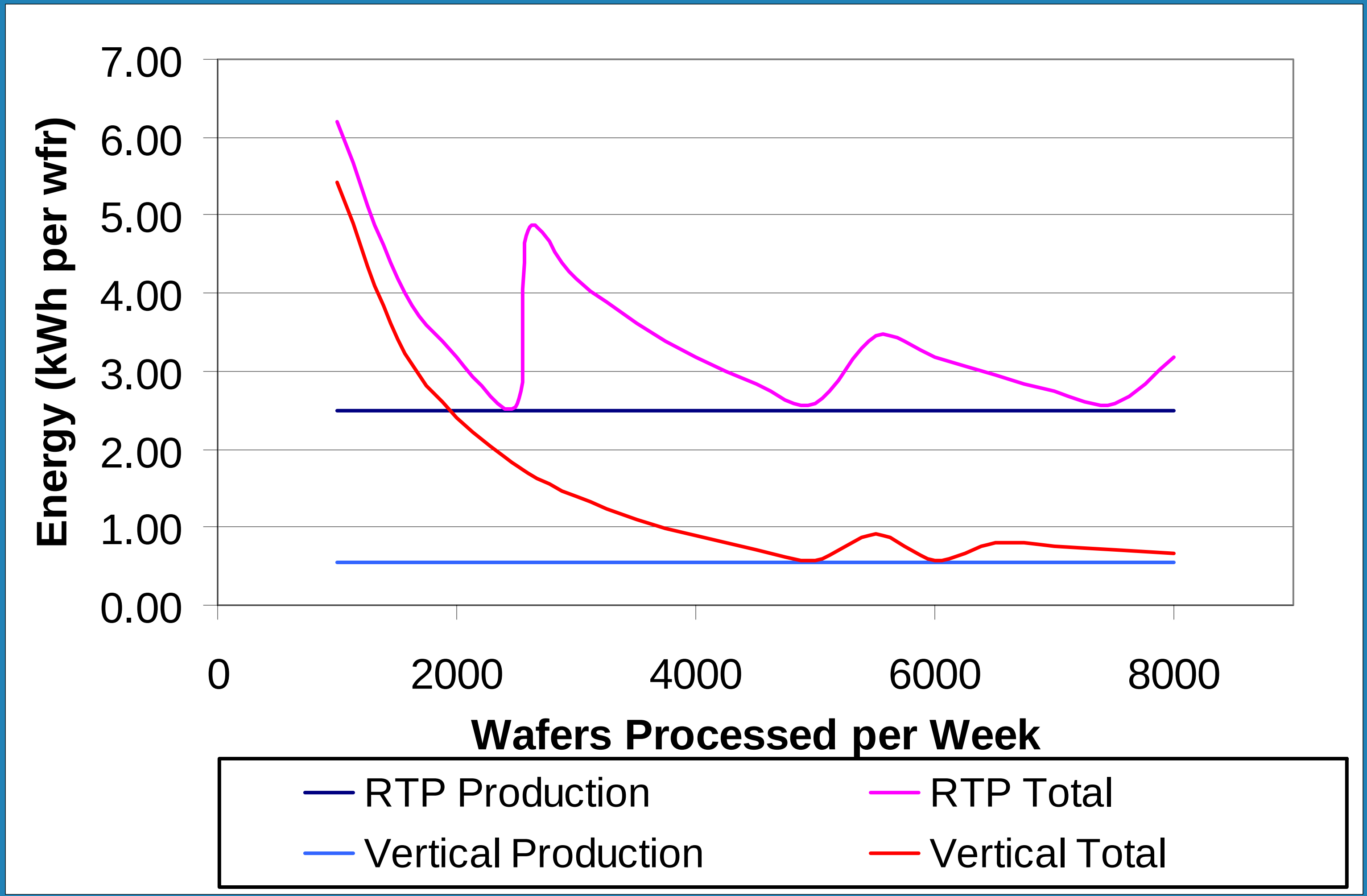
Energy Consumption as Function of Time

$$Time_{equip\ demand} = \frac{\text{(wafers / week) (hours / run)}}{\text{wafers / run}}$$

$$Units_{equip} = \text{Roundup}\left[(Time_{equip\ demand}) / Time_{prod}\right]$$

$$\text{Time}_{idle} = (Units_{equip} \times Time_{prod}) - Time_{equip\ demand}$$

Effects of Equipment on Furnace Unit Operation

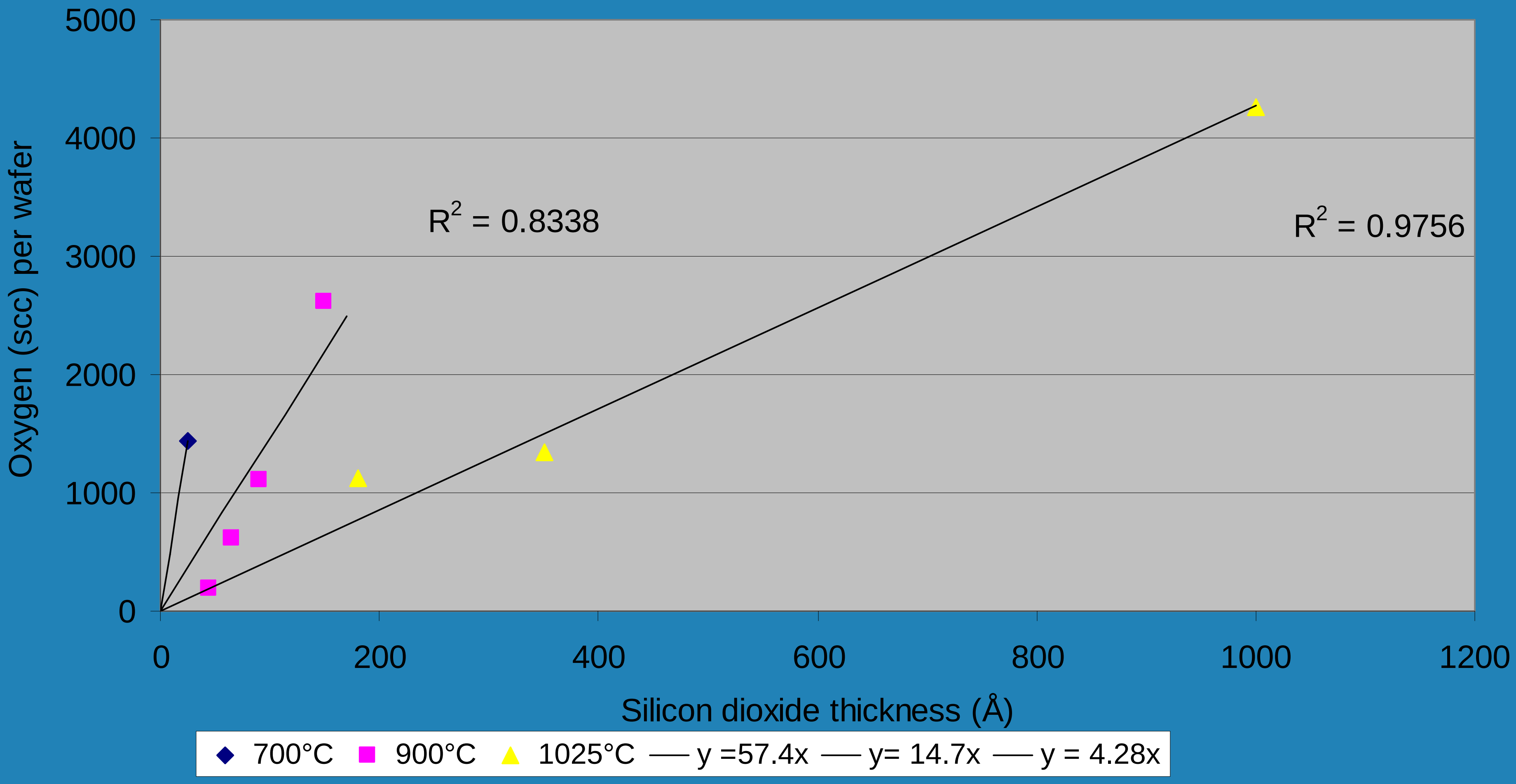


Effects of Process Design on Furnace Unit Operation

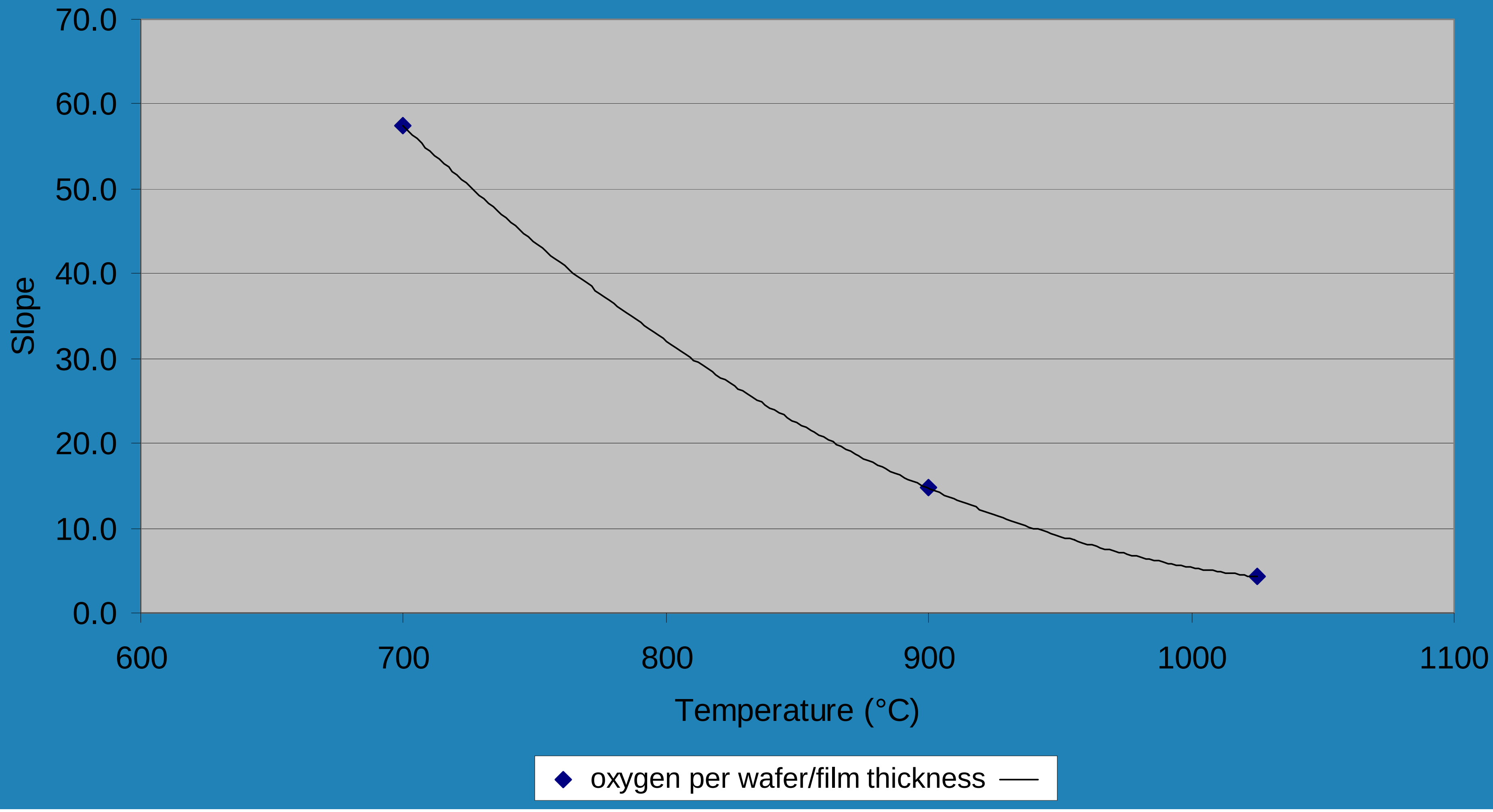
- Same equipment type (vertical furnace)
- Same function (growing SiO_2 on bare silicon – dry oxidation)
- Three different temperatures, eight different thickness

Given any temperature between 700 and 1025ºC and thickness between 25 and 1000 Å, can we predict the amount of oxygen consumed?

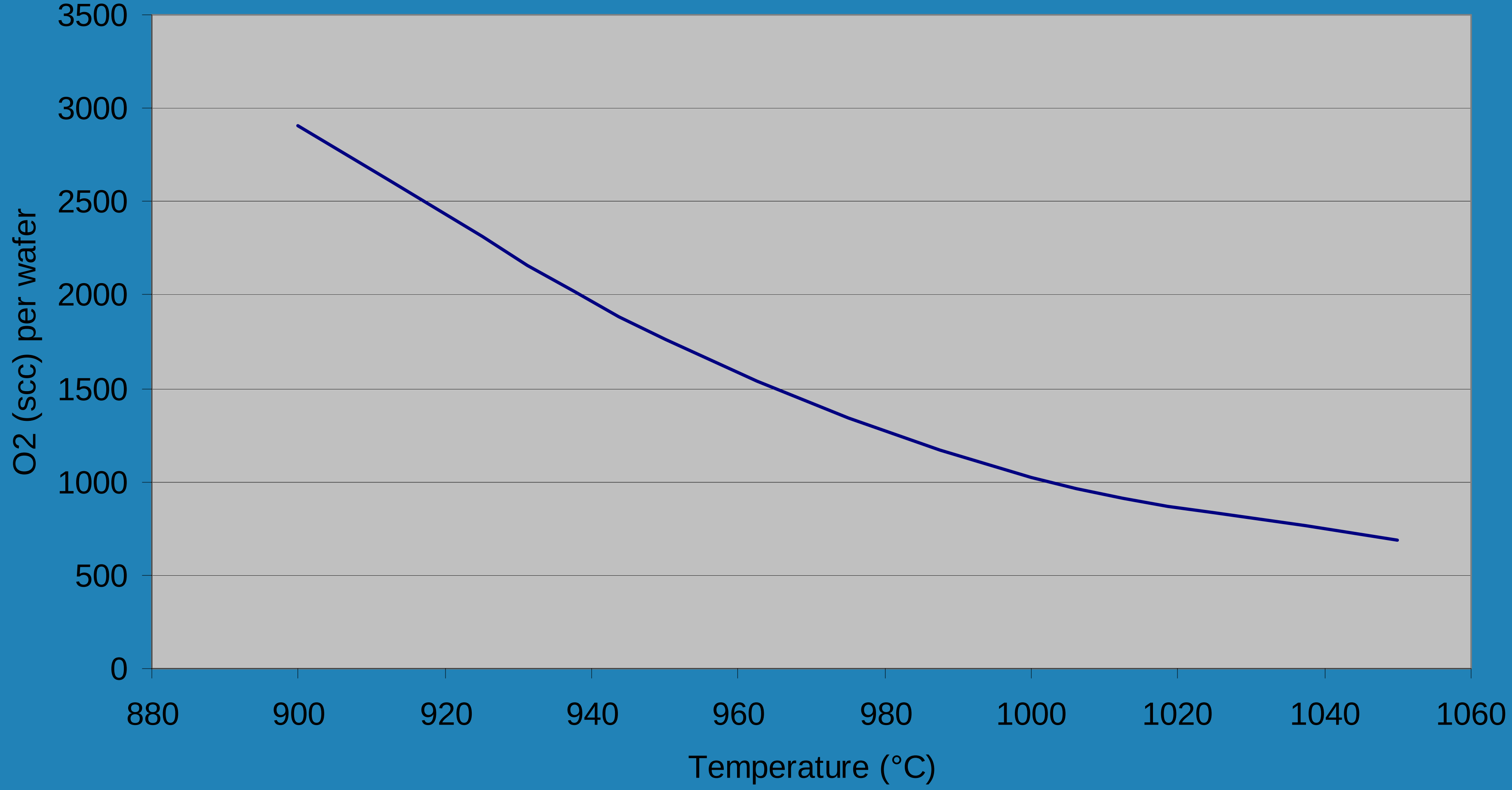
Oxygen Consumption vs. Thickness for 3 Different Temperatures



Oxygen / Thickness vs. Temperature



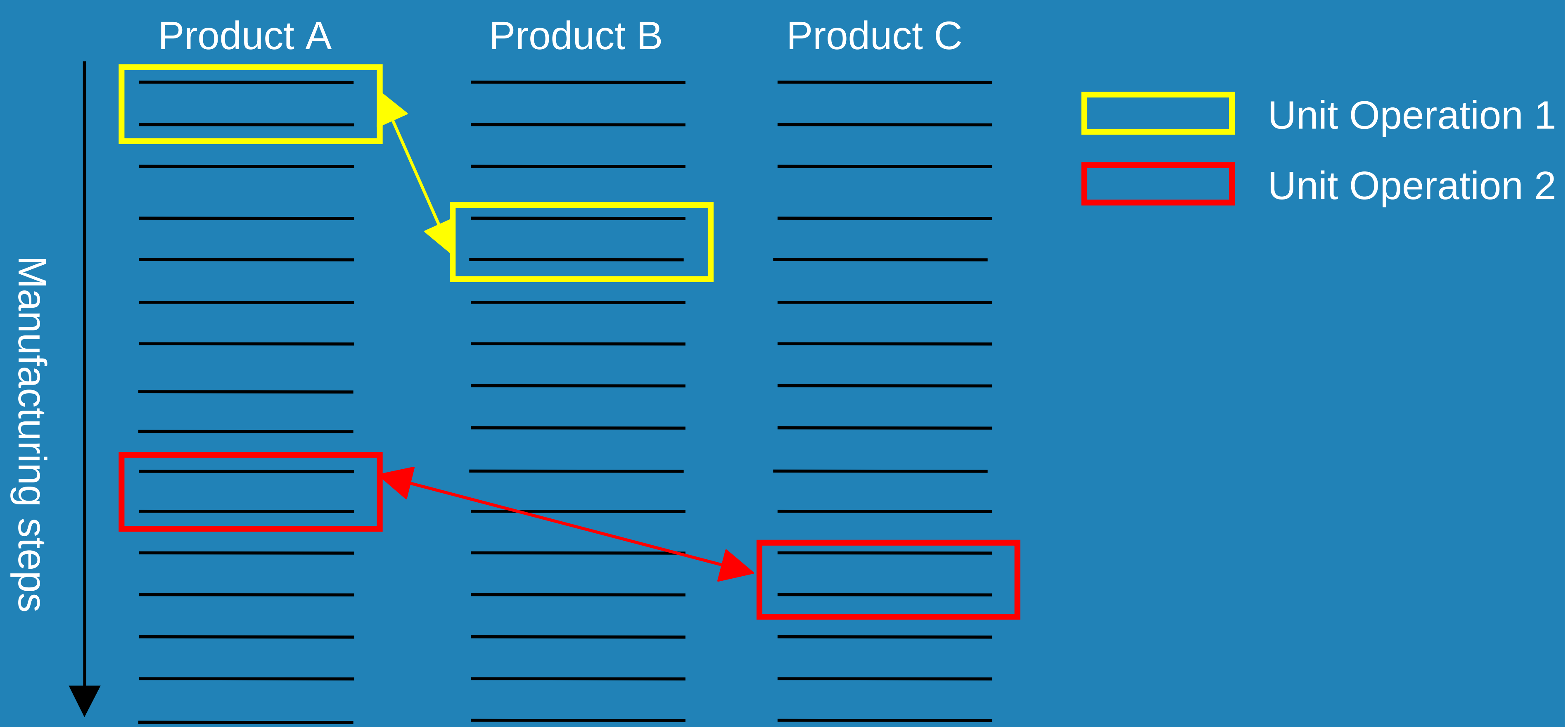
Oxygen Consumption vs. Temperature for a 200 Å Oxide



O_2 (scc) = $(0.0004T^2 - 0.8542T + 459.12)$ x thickness (Å)

Scenario 2

- Process engineer wants to drop temperature from 1025ºC to 950ºC on a 200 Å oxide layer in order to improve process control
- Question – How does decreasing the temperature affect oxygen consumption?
- Answer –
  - At 1025ºC, 804 sccs of O2 are consumed
  - At 950ºC, 1764 sccs of O2 are consumed (more than double)

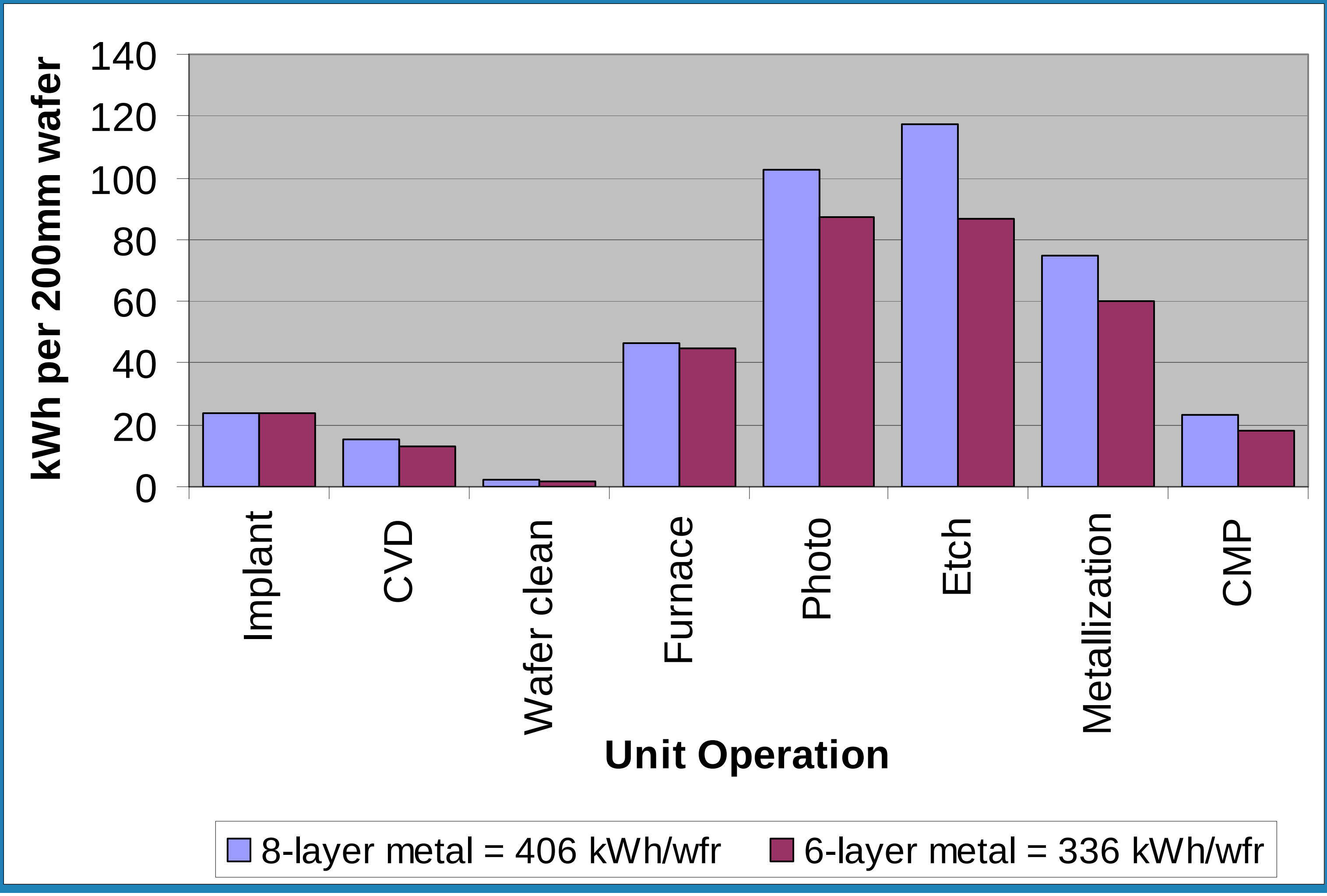


- Characterize a “typical” process within a given unit operation
- Vary for specific products or process flows as needed based on known relationships between consumption and/or emissions and key design parameters

Aggregation of Unit Operation Data

Unit Operation	Number of functions		Wafers per run	Wafers per hour	Power (kW)	
	8 layer	6 layer			Proc	Idle
Implant	16	16	25	20	27	15
CVD	13	11	10	15	16	14
Wafer	35	31	50	150	8	7.5
Furnace	21	17	150	35	21	16
Furnace	7	7	1	10	48	45
Photo	27	23	1	60	115	48
Photo	27	23	1	60	90	37
Etch	24	20	1	35	135	30
Etch (ash)	27	23	1	20	1	0.8
Metalliz'n	11	9	1	25	150	83
CMP	18	14	1	25	29	8

Energy Requirements for 8 vs. 6-Layer Metal MPU



Applications

- Method can be used to quantitatively predict changes in inventory based on product or process design change
- Especially useful for processes that
  - are used repeatedly
  - use significant amounts of bulk chemicals, gases, or water
  - where direct measurement is clumsy or impossible

Impact on Industry

- Industry consortium (SEMATECH) was host to the development of these methodologies and datasets
- Results well received by 12 member companies (major semiconductor companies)
- SEMATECH plans to continue in this area
- Applied Materials, Motorola, AMD, ST Microelectronics interested

Summary

- Inventories that are relatively independent of product type and specific process recipes
  - Allows trade-off analyses to be made
  - Facilitates predictions about environmental consequences as a function of product or process design changes
  - Contain less sensitive or proprietary manufacturing information thus increase potential for sharing of data along the supply chain

Future Work

- Focus on energy-
  - More critical as move to deep UV
  - Assume that it is a reasonable surrogate for material consumption
  - Data is less sensitive and easier to share
  - Critical for economic health of industry
- Look at equipment factory integration (thermal management) as well as energy requirements for process operations
- Work with equipment suppliers