Thermodynamic Analysis of Manufacturing Processes

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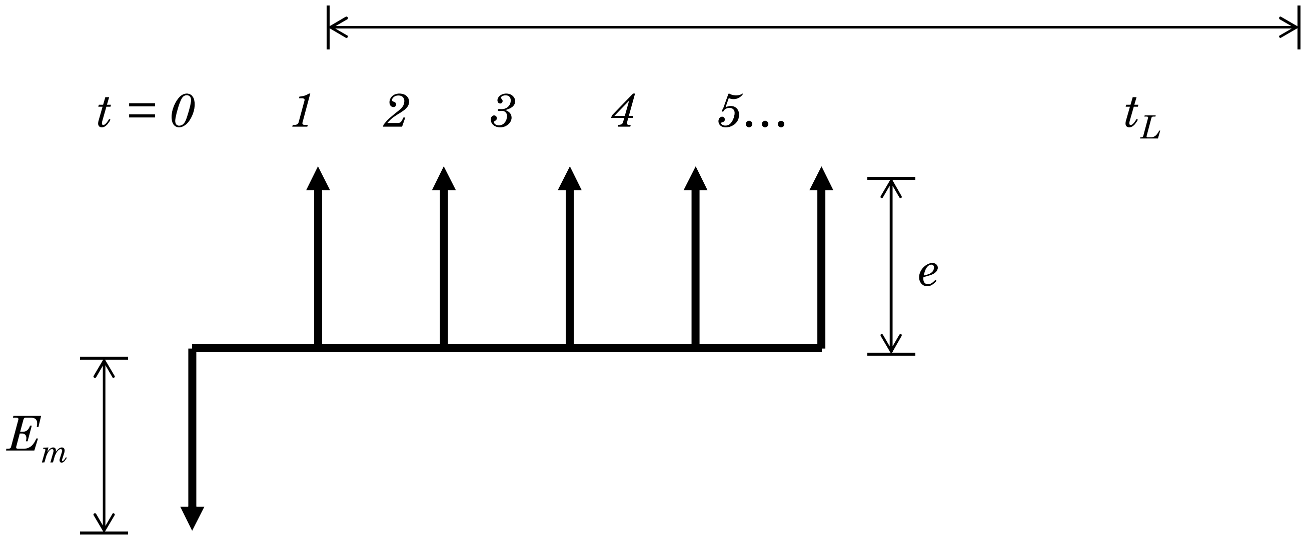
Readings

1. ***Exergy Ch 8***, *Cengel and Boles*
2. ***Appendix,*** *Szargut*
3. ***Thermodynamic Analysis of Resources Used in Manufacturing Processes***, *Gutowski et al*

Role in “New Energy”

Energy Payback



Time to breakeven =

$$t_B = E_m/e$$

Energy Return on Energy Investment =

$$EROI = e t_L/E_m$$

Efficiencies of Energy Production, "e"

$$\eta_{II} = \frac{e_{out}}{e_{avail}}$$

$$e_{out} = \eta_{II} e_{avail}$$

$$\eta_{II}$$

PV: Shockley - Queisser Limit

Wind: Betz Limit

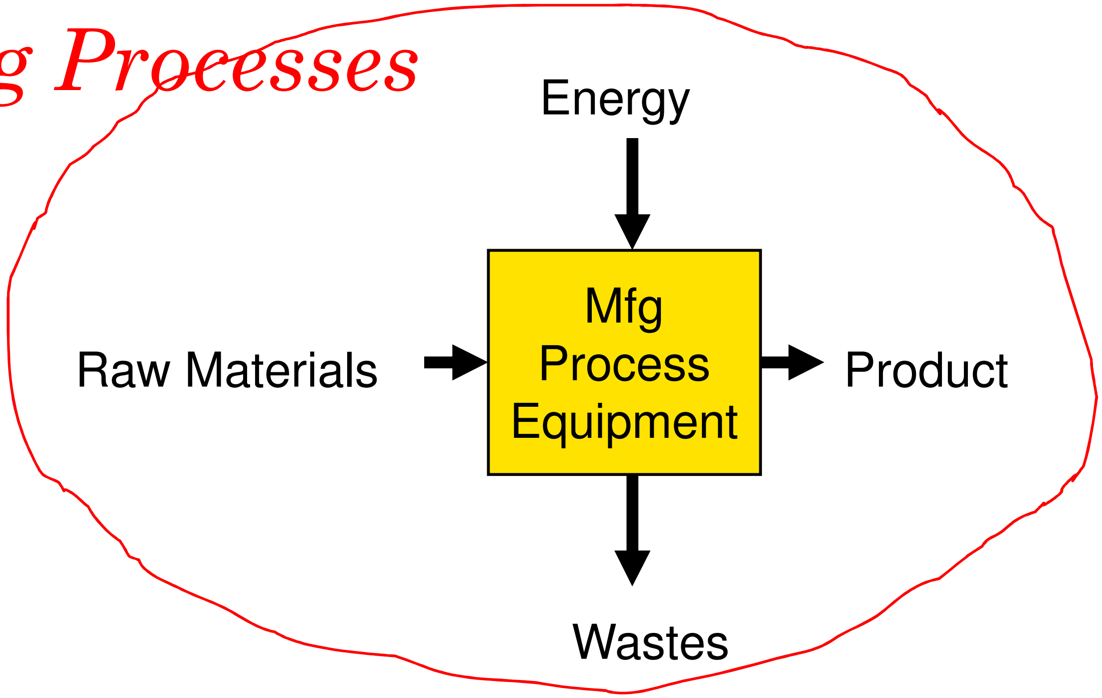
Nuclear: Carnot Limit

Efficiencies of Mfg Energy Requirement, “E_m”

$$\eta = \frac{E_{\min}}{E_{actual}}$$

$$\eta = \;?$$

Thermodynamic Analysis of Resources Used in Manufacturing Processes

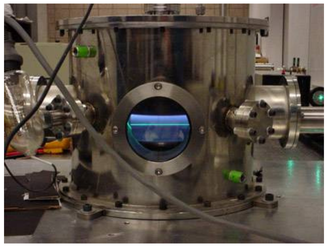

Energy

Mfg Process Equipment

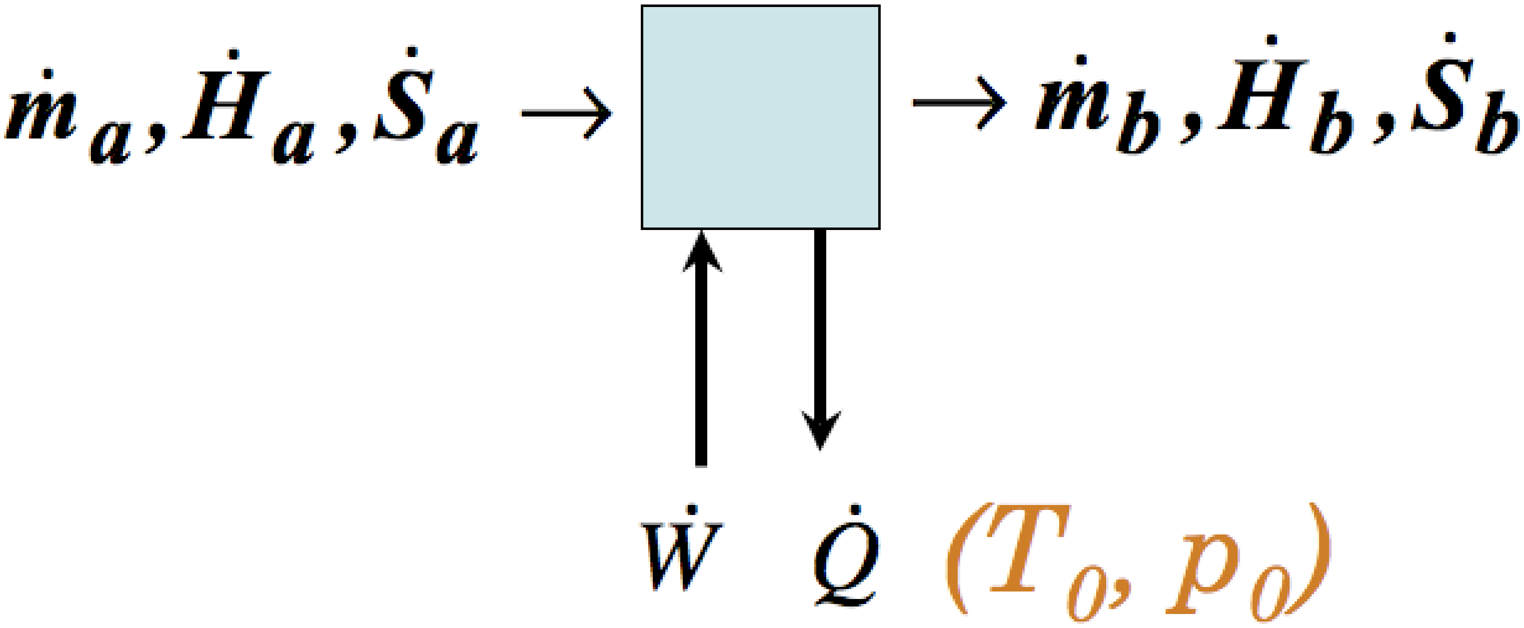
Raw Materials

Product

Wastes



Thermodynamic Analysis: Materials Transformation, Open System



$\dot{m}_a, \dot{H}_a, \dot{S}_a \rightarrow$

$\rightarrow \dot{m}_b, \dot{H}_b, \dot{S}_b$

$\dot{W}$

$\dot{Q}$ (T_0, p_0)

Balance Equations

$$\frac{dM}{dt} = \dot{m}_a - \dot{m}_b = 0, \ (\dot{m}_a = \dot{m}_b = \dot{m}) \qquad \text{steady state}$$

$$\frac{dE}{dt} = \dot{H}_a + \dot{W} - \dot{Q} - \dot{H}_b = 0 \qquad \text{steady state}$$

$$\frac{dS}{dt} = \dot{S}_a - \frac{\dot{Q}}{T_o} - \dot{S}_b + \dot{S}_{irr} = 0 \qquad \text{steady state}$$

Eliminating $\dot{Q}$, gives Work Rate

$$\dot{W} = H_b - H_a - T_o(\dot{S}_b - \dot{S}_a) + T_o\dot{S}_{irr}$$

$$= \dot{H}_b - T_o\dot{S}_b - (\dot{H}_a - T_o\dot{S}_a) + T_o\dot{S}_{irr}$$

$$-(\dot{H}_o - T_o\dot{S}_o) + (\dot{H}_o - T_o\dot{S}_o)$$

$$\dot{W} = \dot{B}_b - \dot{B}_a + T_o\dot{S}_{irr}$$

In terms of Minimum Work

$$\dot{W} = \dot{B}_b - \dot{B}_a + T_o\dot{S}_{irr}$$

*F*or the ideal case "reversible process"

$$(T_o\dot{S}_{irr} = 0) \qquad w_{min} = \frac{\dot{W}}{\dot{m}} = b_b - b_a$$

intensive form, exergy per mole or mass, or

extensive form $W_{min} = B_b - B_a$

Exergy

$$B = (H - T_o S) - (H_o - T_o S_o)$$

$$B = (H - H_o) - T_o\,(S - S_o)$$

$$dB = dH - T_o dS$$

B, X, Ex, $\mathbf{E}$, ε

Open Systems, approximations for temperature and pressure dependence

- Condensed phases

$$dh = c\, dT + v\, dp$$

$$ds = c\, dT/T$$

- Ideal gases

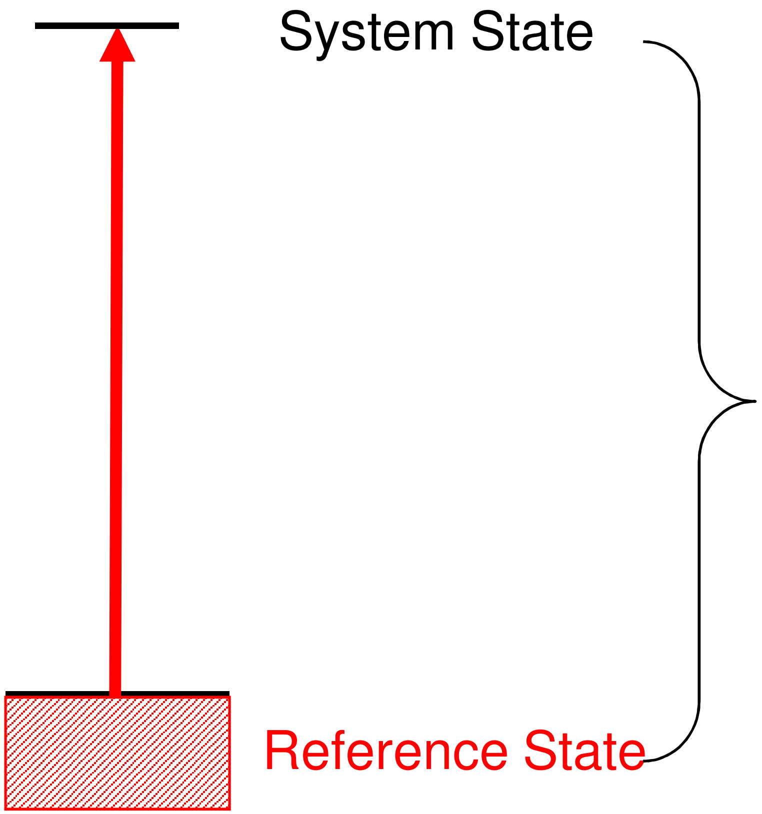
$$dh = c_p\, dT$$

$$ds = c_p\, dT/T - R\, dp/p$$

Definition of Exergy “B”

“Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature” [Szargut et al 1988].

Exergy

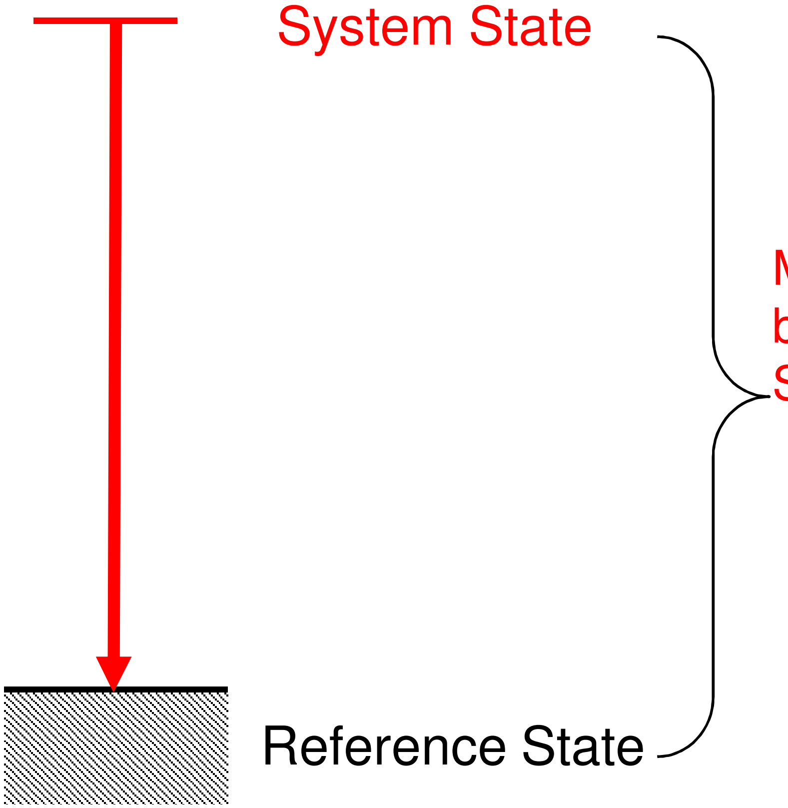


System State

Reference State

Maximum work obtainable between System and Reference States; or minimum work needed to raise System from the reference state to the System State

Exergy



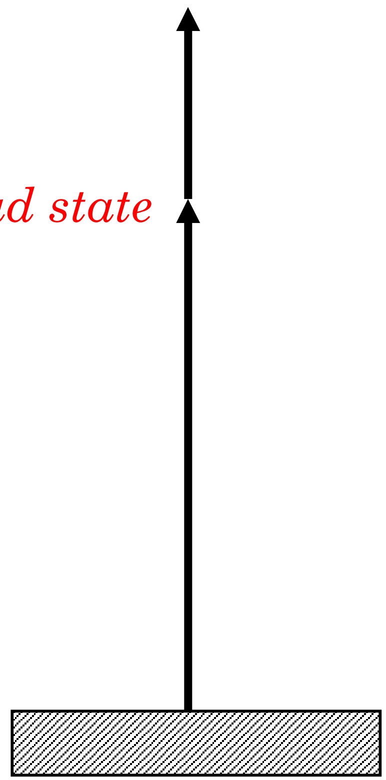
System State

Maximum work obtainable between System and Reference States.

Reference State

Types of Exergy

- Flow exergy (open systems)
  - – Chemical
  - – Mechanical
    - Temperature
    - Pressure
    - Kinetic energy
    - Potential energy
- Work interaction
- Heat interaction



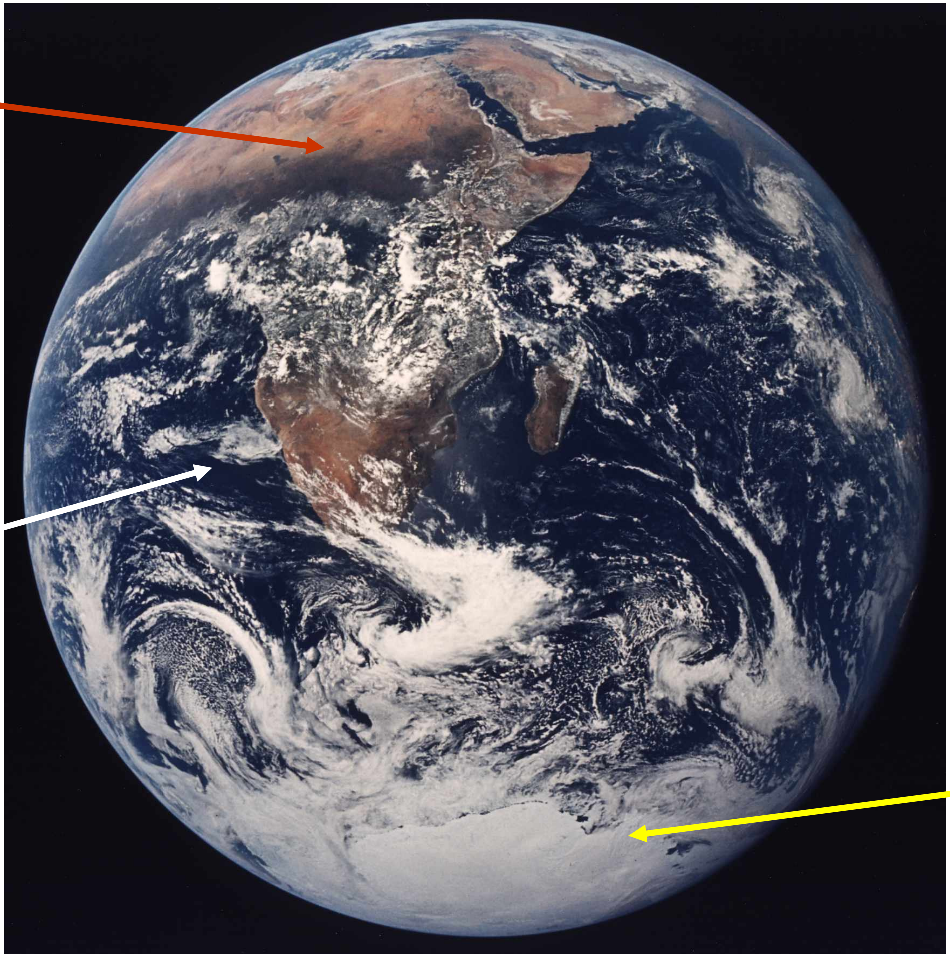
Restricted dead state
To, Po

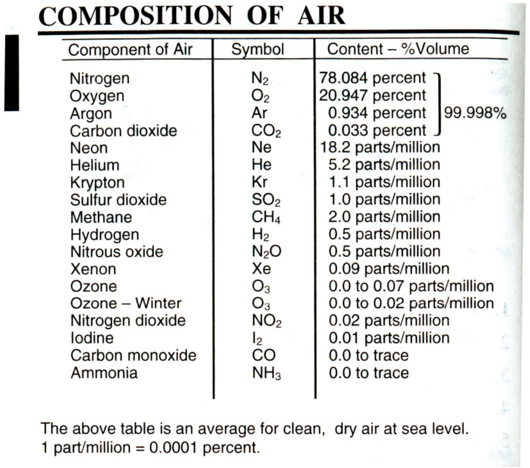
Dead state, e.g earth's crust
at To, Po

Chemical Properties referenced to the “environment”

Crust

Oceans





COMPOSITION OF AIR

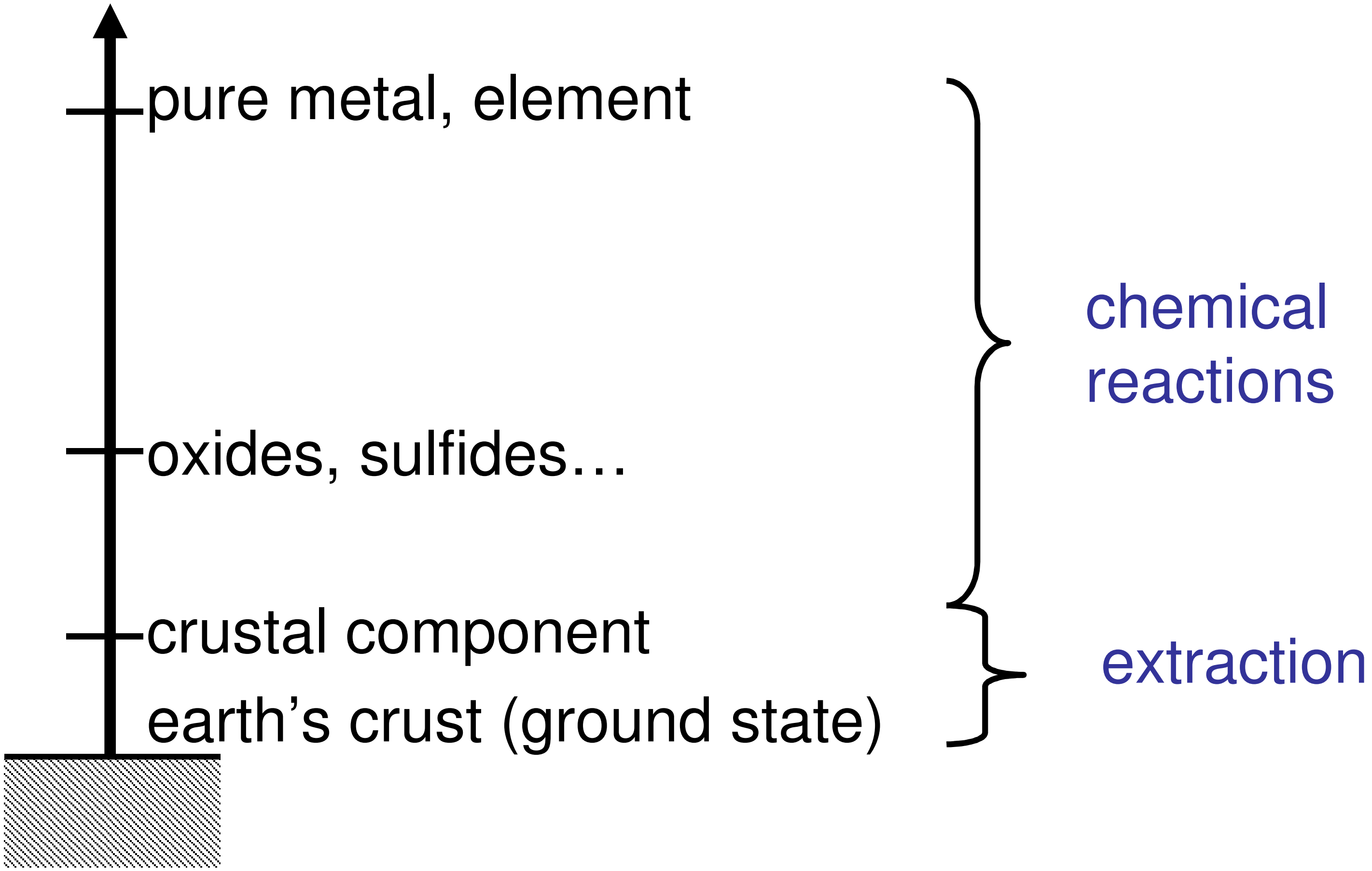
Component of Air	Symbol	Content – %Volume	
Nitrogen	N_2	78.084 percent	99.998%
Oxygen	O_2	20.947 percent	
Argon	Ar	0.934 percent	
Carbon dioxide	CO_2	0.033 percent	
Neon	Ne	18.2 parts/million	
Helium	He	5.2 parts/million	
Krypton	Kr	1.1 parts/million	
Sulfur dioxide	SO_2	1.0 parts/million	
Methane	CH_4	2.0 parts/million	
Hydrogen	H_2	0.5 parts/million	
Nitrous oxide	N_2O	0.5 parts/million	
Xenon	Xe	0.09 parts/million	
Ozone	O_3	0.0 to 0.07 parts/million	
Ozone – Winter	O_3	0.0 to 0.02 parts/million	
Nitrogen dioxide	NO_2	0.02 parts/million	
Iodine	I_2	0.01 parts/million	
Carbon monoxide	CO	0.0 to trace	
Ammonia	NH_3	0.0 to trace	

The above table is an average for clean, dry air at sea level.
1 part/million = 0.0001 percent.

Atmosphere

T_0 = 298.2 K, P_0 = 101.3 kPA

Exergy Reference System



pure metal, element

oxides, sulfides…

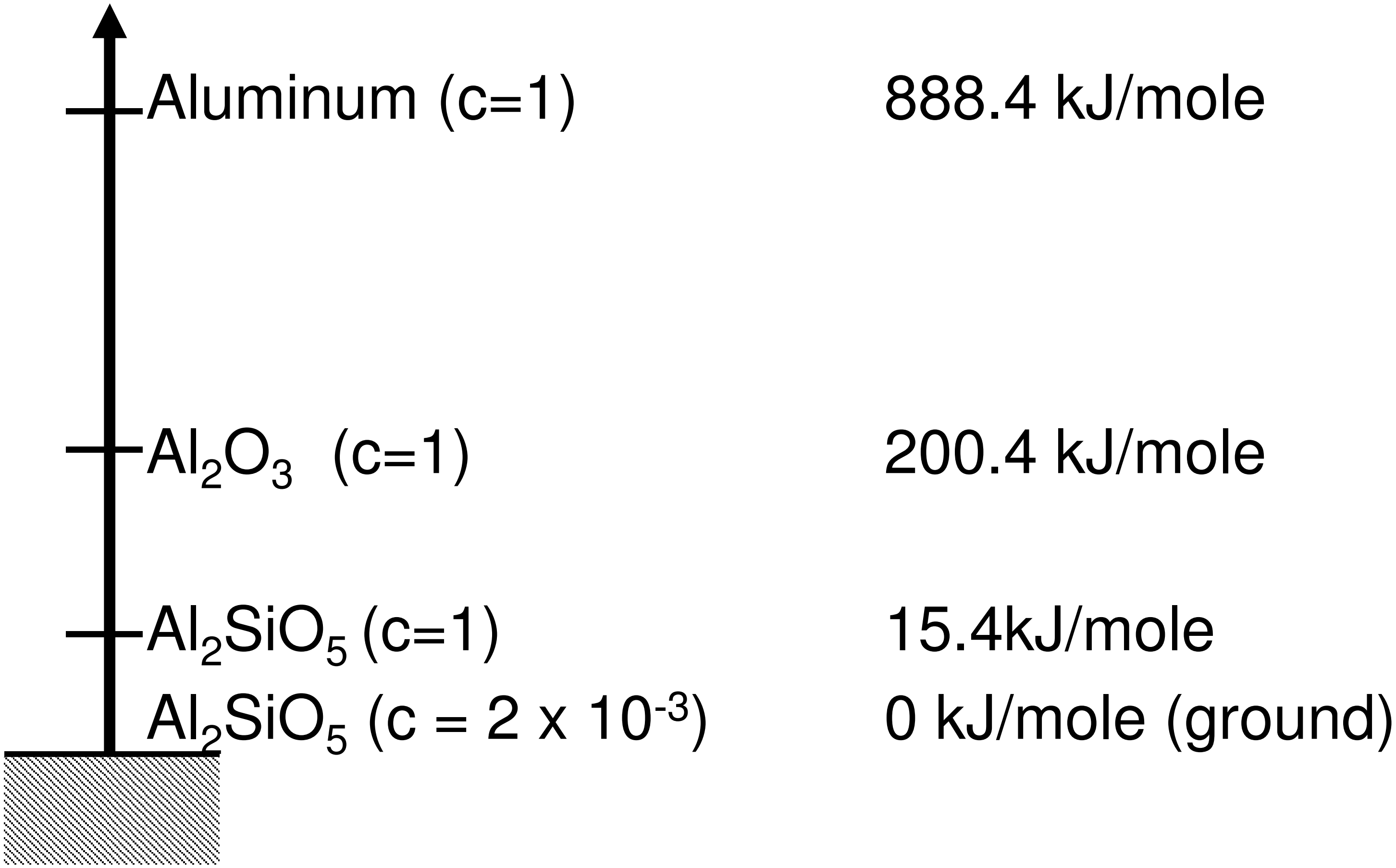
crustal component

earth’s crust (ground state)

chemical reactions

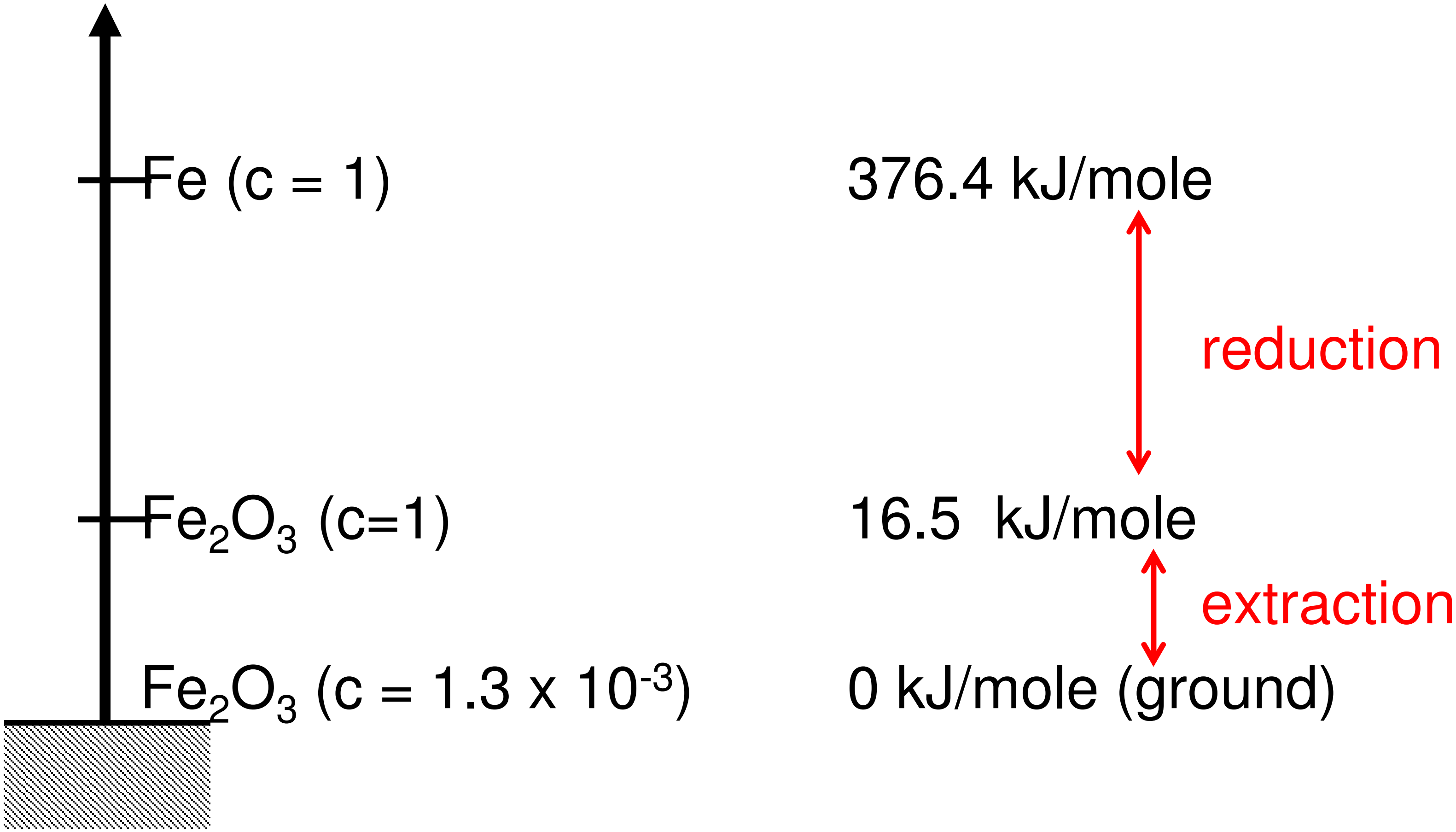
extraction

Exergy Reference System



Aluminum (c=1)	888.4 kJ/mole
Al_2O_3 (c=1)	200.4 kJ/mole
Al_2SiO_5 (c=1)	15.4kJ/mole
Al_2SiO_5 ($c = 2 \times 10^{-3}$)	0 kJ/mole (ground)

Example; making pure iron from the crust



Fe (c = 1) 376.4 kJ/mole

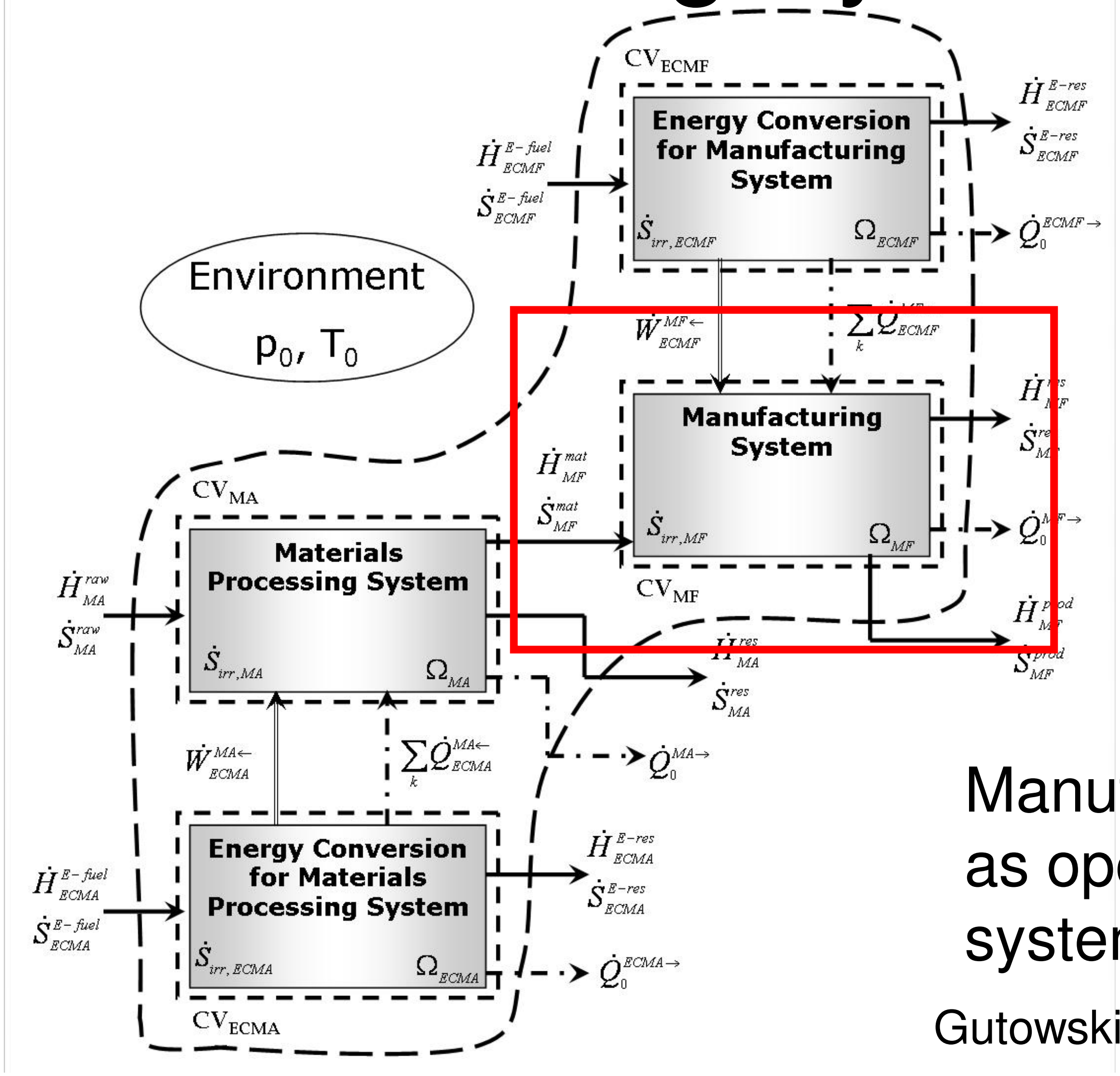
reduction

Fe_2O_3 (c=1) 16.5 kJ/mole

extraction

Fe_2O_3 (c = 1.3×10^{-3}) 0 kJ/mole (ground)

Mfg Systems



Manufacturing Systems as open thermodynamic systems

Gutowski et al ES&T 2009

Balances for Mfg Process

Mass

$$\frac{dm_{MF}}{dt} = \left(\sum_{i=1} \dot{N}_{i,in} M_i\right)_{MF} - \left(\sum_{i=1} \dot{N}_{i,out} M_i\right)_{MF}$$

Energy

$$\frac{dE_{MF}}{dt} = \sum_i \dot{Q}_{ECMF}^{MF\leftarrow} - \dot{Q}_0^{MF\rightarrow} + \dot{W}_{ECMF}^{MF\leftarrow} + \dot{H}_{MF}^{mat} - \dot{H}_{MF}^{prod} - \dot{H}_{MF}^{res}$$

Entropy

$$\frac{dS_{MF}}{dt} = \sum_i \frac{\dot{Q}_{ECMF}^{MF\leftarrow}}{T_i} - \frac{\dot{Q}_0^{MF\rightarrow}}{T_0} + \dot{S}_{MF}^{mat} - \dot{S}_{MF}^{prod} - \dot{S}_{MF}^{res} + \dot{S}_{irr,MF}$$

Work Rate for Mfg Process in Steady State

$$\dot{W}_{ECMF}^{MF\leftarrow} = ((\dot{H}_{MF}^{prod} + \dot{H}_{MF}^{res}) - \dot{H}_{MF}^{mat})$$

$$-T_0((\dot{S}_{MF}^{prod} + \dot{S}_{MF}^{res}) - \dot{S}_{MF}^{mat})$$

$$-\sum_{i>0}\left(1 - \frac{T_0}{T_i}\right)\dot{Q}_{ECMF}^{MF\leftarrow} + T_0\dot{S}_{irr,MF}$$

Exergy and Work

$$B = (H - T_o S) - (H - T_o S)_o$$

$$\dot{W}^{MF\leftarrow}_{ECMF} = ((\dot{B}^{prod}_{MF} + \dot{B}^{res}_{MF}) - \dot{B}^{mat}_{MF}) - \sum_{i>0}\left(1 - \frac{T_0}{T_i}\right)\dot{Q}^{MF\leftarrow}_{ECMF} + T_0 \dot{S}_{irr,MF}$$

Branham et al IEEE ISEE 2008

Examples: plastic work, melting, vaporizing etc.

Physical & Chemical Exergy

$$\dot{W}_{ECMF}^{MF\leftarrow} = \cancel{((\dot{B}_{MF}^{prod} + \dot{B}_{MF}^{res}) - \dot{B}_{MF}^{mat})^{ph}}$$

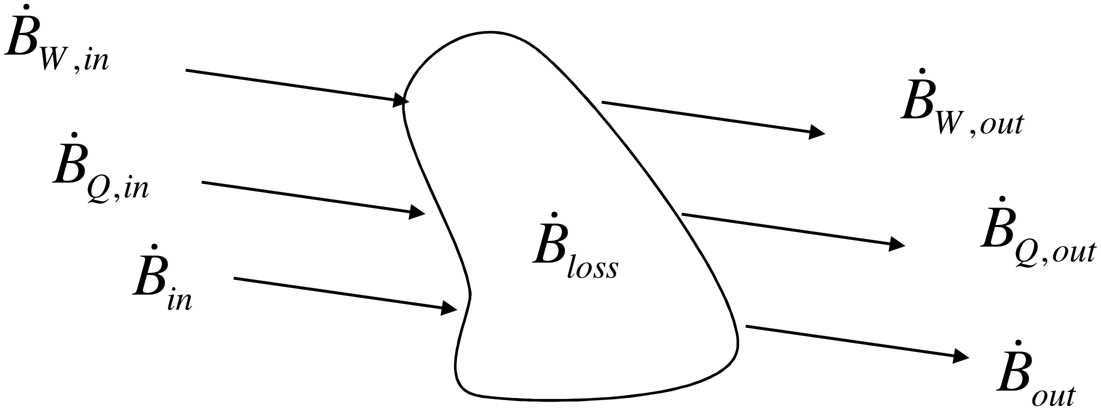
$$+ (\sum_{i=1}^{n} b_i^{ch} \dot{N}_i)_{MF}^{prod} + (\sum_{i=1}^{n} b_i^{ch} \dot{N}_i)_{MF}^{res} -$$

$$(\sum_{i=1}^{n} b_i^{ch} \dot{N}_i)_{MF}^{mat} - \cancel{\sum_{i>0} \left(1 - \frac{T_0}{T_i}\right)} \dot{Q}_{ECMF}^{MF\leftarrow} + T_0 \dot{S}_{irr,MF}$$

*Here all chemical exergy terms (**b^{ch}**) are at T_o, P_o*

Branham et al IEEE ISEE 2008

Exergy Balance, Open System



$$\dot{B}_{in} + \dot{B}_{W,in} + \dot{B}_{Q,in} = \dot{B}_{out} + \dot{B}_{W,out} + \dot{B}_{Q,out} + \dot{B}_{loss}$$

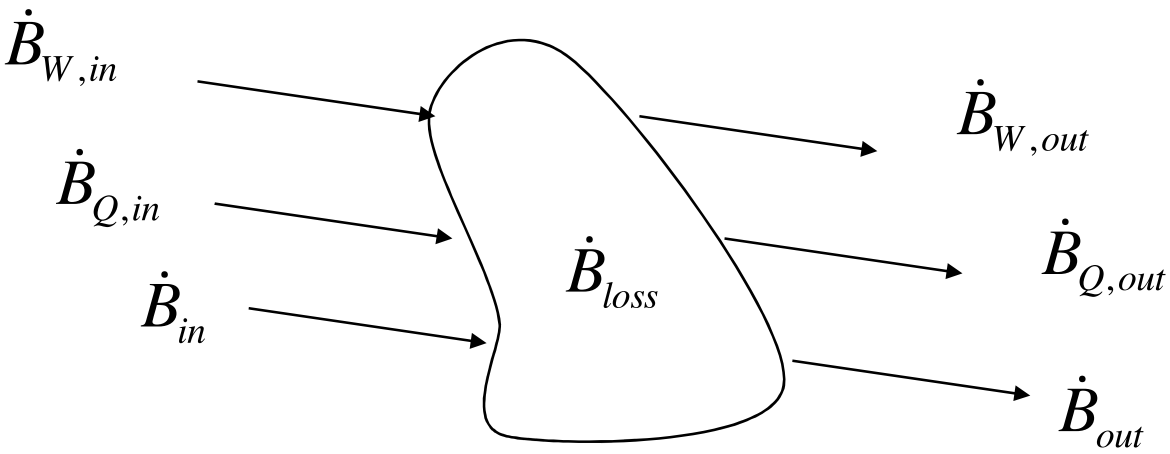
Includes: materials flows, heat and work interactions

Example Calculations Second Law Efficiency

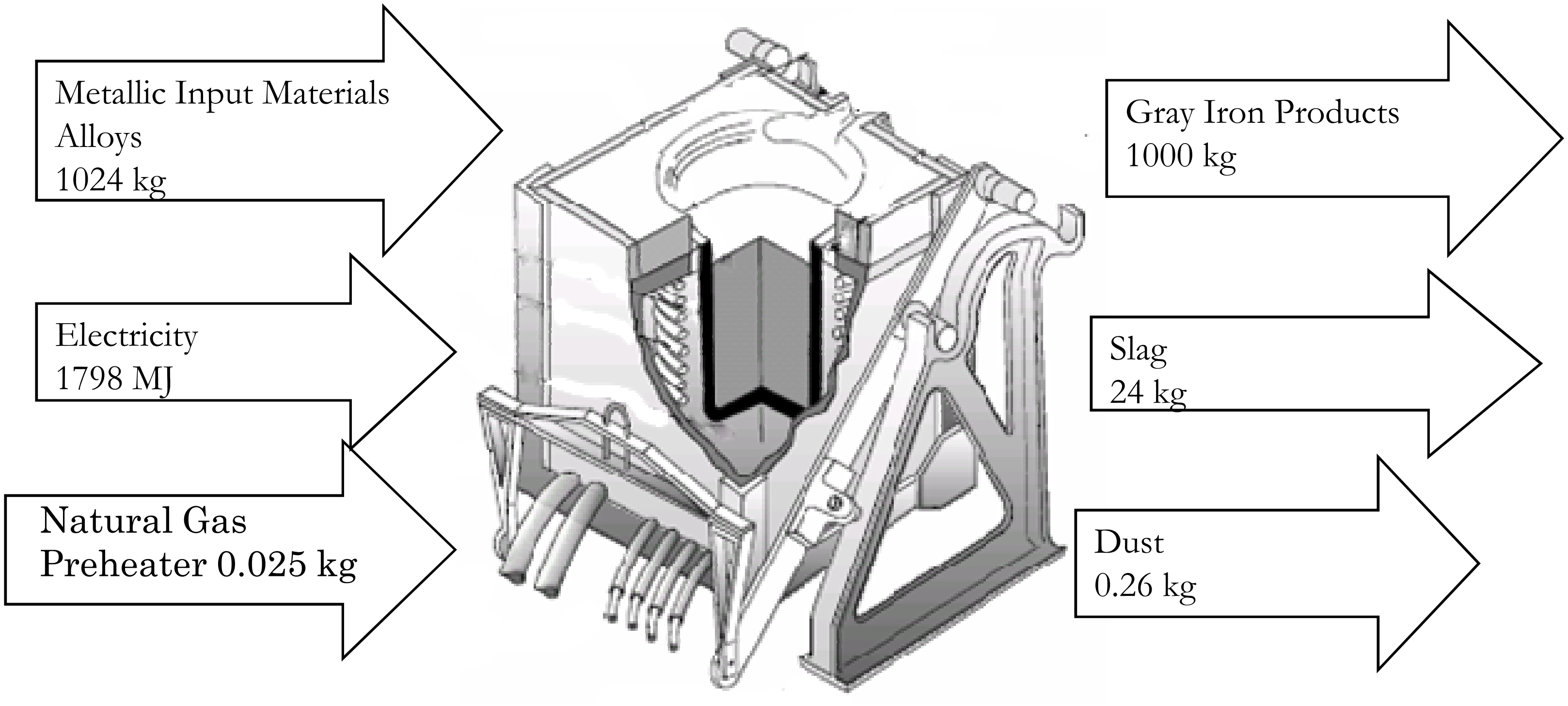
- Melting of iron
- Machining
- CVD of SiO_2
- Thermal Oxidation of SiO_2
- High Pressure SWCNT

Second Law Efficiency

$$\eta_p = \frac{B_{useful\ output}}{B_{in}} \qquad \eta = \frac{W_{\min}}{W_{actual}}$$



Induction Melting Exergy Analysis



Metallic Input Materials
Alloys
1024 kg

Electricity
1798 MJ

Natural Gas
Preheater 0.025 kg

Gray Iron Products
1000 kg

Slag
24 kg

Dust
0.26 kg

Boundaries are drawn around the entire facility,
all components are at standard pressure and temperature

Batch Induction Melter Exergy Analysis*

Ductile Iron Batch Electric Induction Melting

Material	Amount (kg)	Weight Percent	Standard Chemical Exergy (MJ/kg)	Exergy (MJ)	Percent Total Exergy
Input Materials					
Steel Scrap	439	42.85%	6.89	3022.25	15.39%
Pig Iron	1.6	0.16%	8.18	13.43	0.07%
Ductile Iron Remelt	535	52.25%	8.44	4513.98	22.99%
65% Silicon Carbide Briquettes	4.3	0.42%	31.73	137.62	0.70%
75% Ferrosilicon	3.0	0.29%	24.51	72.46	0.37%
5% MgFeSi	14.8	1.44%	19.09	282.30	1.44%
Copper	1.7	0.17%	2.11	3.69	0.02%
Tin	0.005	0.00%	1.13	0.01	0.00%
62% Fe-Molybdenum	6.2	0.61%	7.28	45.35	0.23%
Carbon 9012	18	1.80%	34.16	628.45	3.20%
Natural Gas Preheater	0.02	0.00%	51.84	1.27	0.01%
Electricity				5418.00	55.59%
Total Inputs	**1024**	**100.00%**		**14138.83**	**100.00%**
Output Materials					
Ductile Iron Melt	1000.2	96.69%	8.44	8436.45	99.29%
Slag	33.9	3.28%	1.14	60.05	0.71%
Dust	0.3	0.02%	0.26	0.07	0.00%
Total Outputs	**1034**	**100.00%**		**8497**	**100.00%**
Mass Difference	**-1.05%**				

*including losses at Utility

Batch Electric Degree of Perfection

$$\eta_P = \frac{Exergy\ of\ useful\ products}{Exergy\ of\ inputs}$$

Total Exergy In

(Bin) = **11,155,000 J**

Batch Electric

Induction Melting

of 1 kg of melt

Useful Exergy Out

(Bout) = 8,250,000J

Degree of Perfection

$$\eta_P = \frac{8{,}250{,}000 J}{10{,}420{,}000 J} = 0.79$$

Component	Exergy in (J)
Metallics	8,700,000
Electricity*	1,806,000

*not including utility losses

Minimum work

$$dw = dh - To\ ds$$

$$dw = C\ dT - c\ dT/T$$

$$w = c(T - T_o) - T_o\ c\ \ln(T/T_o) + h_{fusion}(1 - T_o/T_m)$$

Using $Tm = 1540C$, $c = 0.67\ J/gK$ and

$H_{fusion} = 272.15\ J/g$

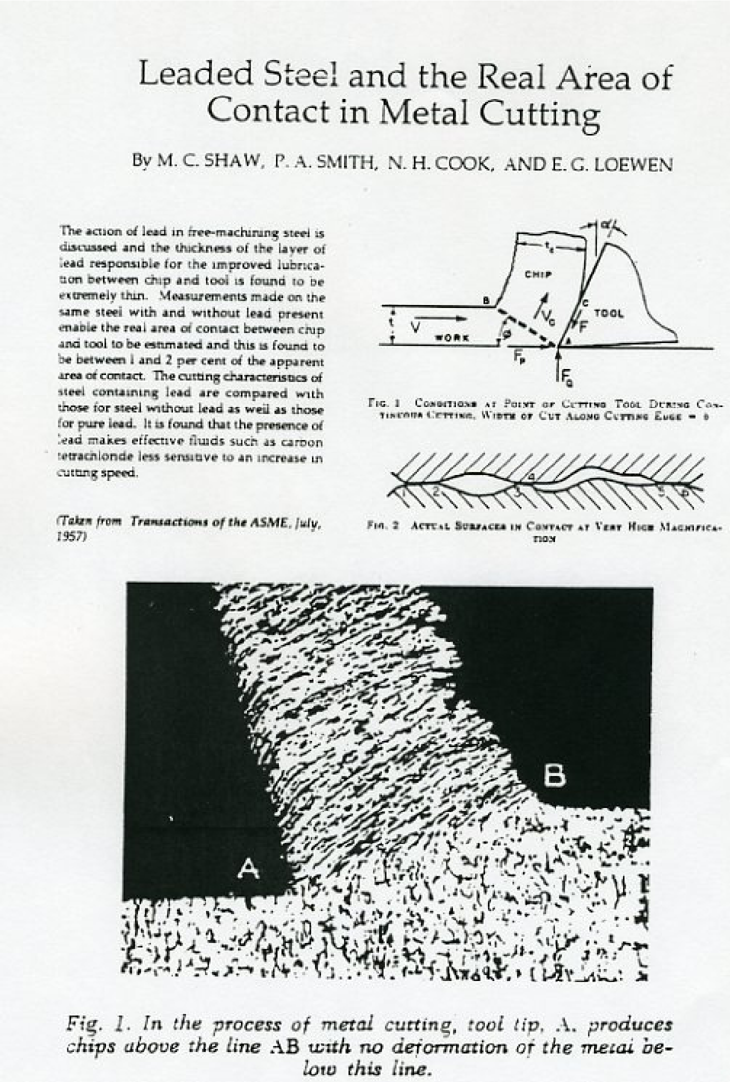
$$w_{min} = 889 J/g = 0.9\ MJ/kg$$

$$w_{actual} = 5.4\ MJ/kg/3 = 1.8\ MJ/kg$$

$$\eta = 0.9/1.8 = 50\%$$

Machining

QuickTime™ and a
decompressor
are needed to see this picture.



Leaded Steel and the Real Area of Contact in Metal Cutting

By M. C. SHAW, P. A. SMITH, N. H. COOK, AND E. G. LOEWEN

The action of lead in free-machining steel is discussed and the thickness of the layer of lead responsible for the improved lubrication between chip and tool is found to be extremely thin. Measurements made on the same steel with and without lead present enable the real area of contact between chip and tool to be estimated and this is found to be between 1 and 2 per cent of the apparent area of contact. The cutting characteristics of steel containing lead are compared with those for steel without lead as well as those for pure lead. It is found that the presence of lead makes effective fluids such as carbon tetrachloride less sensitive to an increase in cutting speed.

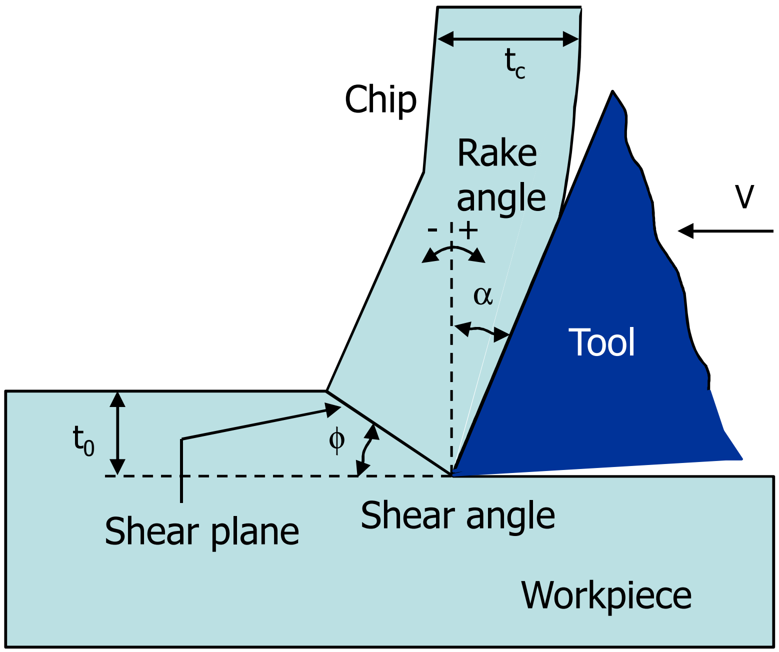
(Taken from Transactions of the ASME, July, 1957)

Fig. 1 Conditions at Point of Cutting Tool During Continuous Cutting, Width of Cut Along Cutting Edge = b

Fig. 2 Actual Surfaces in Contact at Very High Magnification

Fig. 1. In the process of metal cutting, tool tip, A, produces chips above the line AB with no deformation of the metal below this line.

Basic Machining Mechanism



$$F \cdot V = \text{Power} = \frac{d(\text{work})}{dt} = \dot{\text{work}}$$

$$\frac{\dot{\text{work}}}{\dot{\text{vol}}} = \text{specific energy} = u_S$$

$$u_S = u_{\text{plastic work}}\ (65 \text{ to } 80\%) + u_{\text{friction}}$$

$$u_p = \int \bar{\sigma}\, d\bar{\varepsilon} \cong \tau\gamma \qquad 2 \le \gamma \le 4$$

$$u_p \cong \tau\gamma \cong \frac{1}{6} H \times (2-4)$$

Approximation

$u_s \sim H$ (Hardness)

Results are in terms of primary energy

	Production Machining Center (2000)		Manual Milling Machine (1985)	
Electricity Breakdown				
Constant start-up operations (idle)	85.2%		31.6%	
Run-time operations (positioning, loading, etc)	3.5%		0% (manual)	
Material removal operations (in cut)	11.3%		69.4%	
Electricity Requirements				
Constant start-up operations (idle)	166 kW		0.7 kW	
Run-time operations (positioning, loading, etc)	6.8 kW		0 kW	
Material removal operations (in cut)	22 kW		2.1 kW	
Machine Use Scenario				
Arbitrary Number of work hours	1000 hours		1000 hours	
Machine uptime	90%		90%	
Machine hours (idle, positioning, or in cut)	900 hours		900 hours	
Percentage of machine hours spent idle	10%		65%	
Machine hours spent idle	90 hours		585 hours	
Active machine hours per 1000 work hours	810 hours		315 hours	
Machining Scenario				
Percentage of machine hours spent positioning	30%		70%	
Machine hours spent positioning	243 hours		221 hours	
Percentage of machine hours spent in cut	70%		30%	
Machine hours spent in cut	567 hours		94.5 hours	
Electricity Use per 1000 work hours				
Constant start-up operations (idle)	149288 kWh		600 kWh	
Run-time operations (positioning, loading, etc)	5471 kWh		0 kWh	
Material removal operations (in cut)	6237 kWh		100 kWh	
Total electricity use per 1000 work hours	160996 kWh		700 kWh	
Electricity Used per Material Removed				
Material Machined	Aluminum	Steel	Aluminum	Steel
Material Removal Rate	20.0 cm^3/sec	4.7 cm^3/sec	1.5 cm^3/sec	0.35 cm^3/sec
Material removed per 1000 work hours	40824000 cm^3	9593640 cm^3	510300 cm^3	119070 cm^3
Electricity used/Material removed	**14.2 kJ/cm^3**	**60 kJ/cm^3**	**4.9 kJ/cm^3**	**21 kJ/cm^3**

Production machining energy Vs production rate

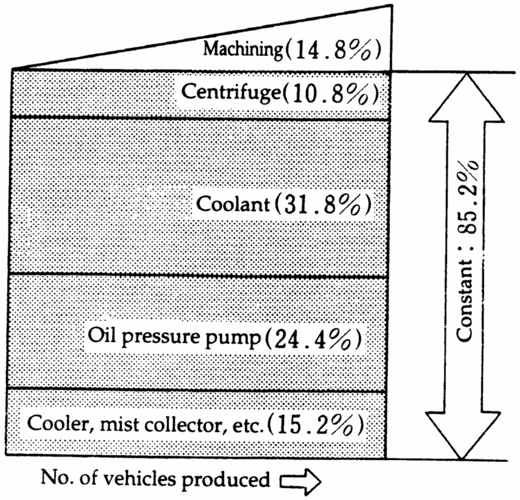


Figure 3.3 Energy Use Breakdown by Type

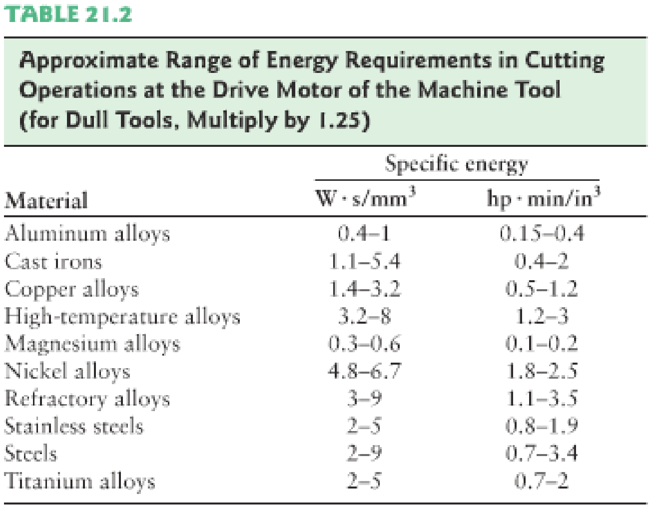


TABLE 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

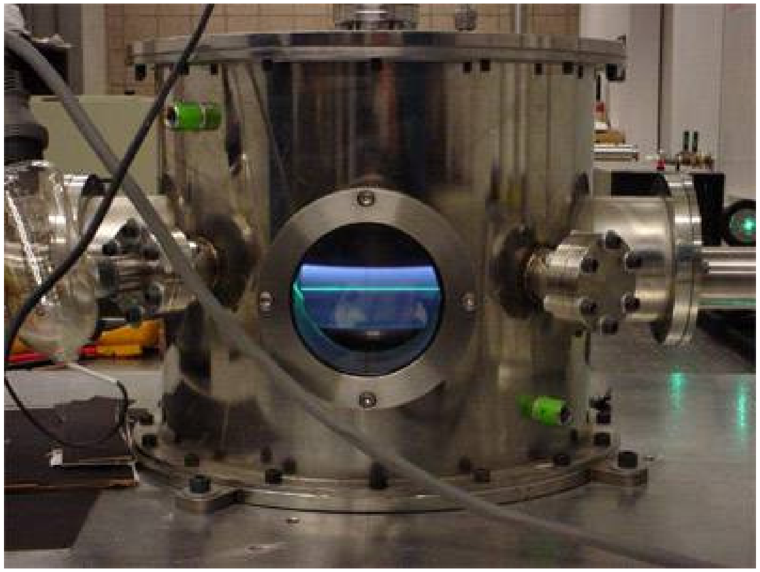
	Specific energy	
Material	W · s/mm³	hp · min/in³
Aluminum alloys	0.4–1	0.15–0.4
Cast irons	1.1–5.4	0.4–2
Copper alloys	1.4–3.2	0.5–1.2
High-temperature alloys	3.2–8	1.2–3
Magnesium alloys	0.3–0.6	0.1–0.2
Nickel alloys	4.8–6.7	1.8–2.5
Refractory alloys	3–9	1.1–3.5
Stainless steels	2–5	0.8–1.9
Steels	2–9	0.7–3.4
Titanium alloys	2–5	0.7–2

$\eta = W_{min}/u_s \approx 0.5$,

Production machining of Aluminum, $\eta = 0.35/14.2/3 = 7.5\%$

Manual machining of aluminum, $\eta = 0.35/4.9/3 = 21\%$

Plasma Enhanced Chemical Vapor Deposition (CVD)



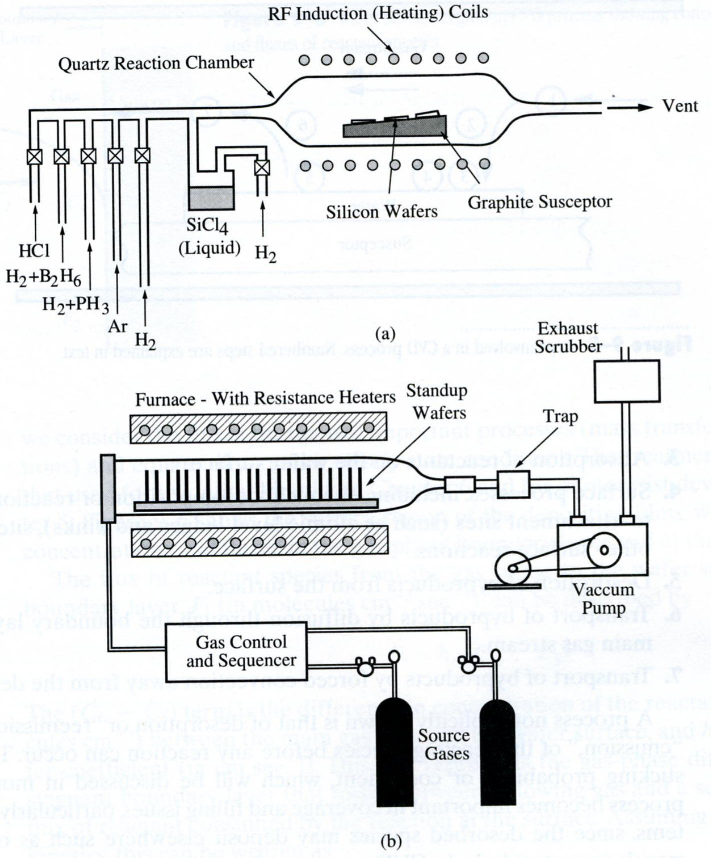


Figure 9–4 Chemical Vapor Deposition (CVD) systems. (a) is an atmospheric cold-wall system used for deposition of epitaxial silicon. (b) is a low-pressure hot-wall system used for deposition of polycrystalline and amorphous films, such as polysilicon and silicon dioxide, respectively.

Plasma enhanced CVD

Input Deposition Gases

Species	*Input mass (g)*	*Input moles or primary energy*	*Exergy (J)*	*%Total Inputs*
SiH4	0.95	0.029579mol	40928.6	0.749
O2	0.49	0.015313mol	60.79	
Ar	0.34	0.008511mol	99.5	
N2	196.9	7.028779mol	4849.9	

Input Cleaning Gases

CH4	69.41	4.326643mol	3598253	63.0
NF3	31.06	0.437453mol	266931.6	

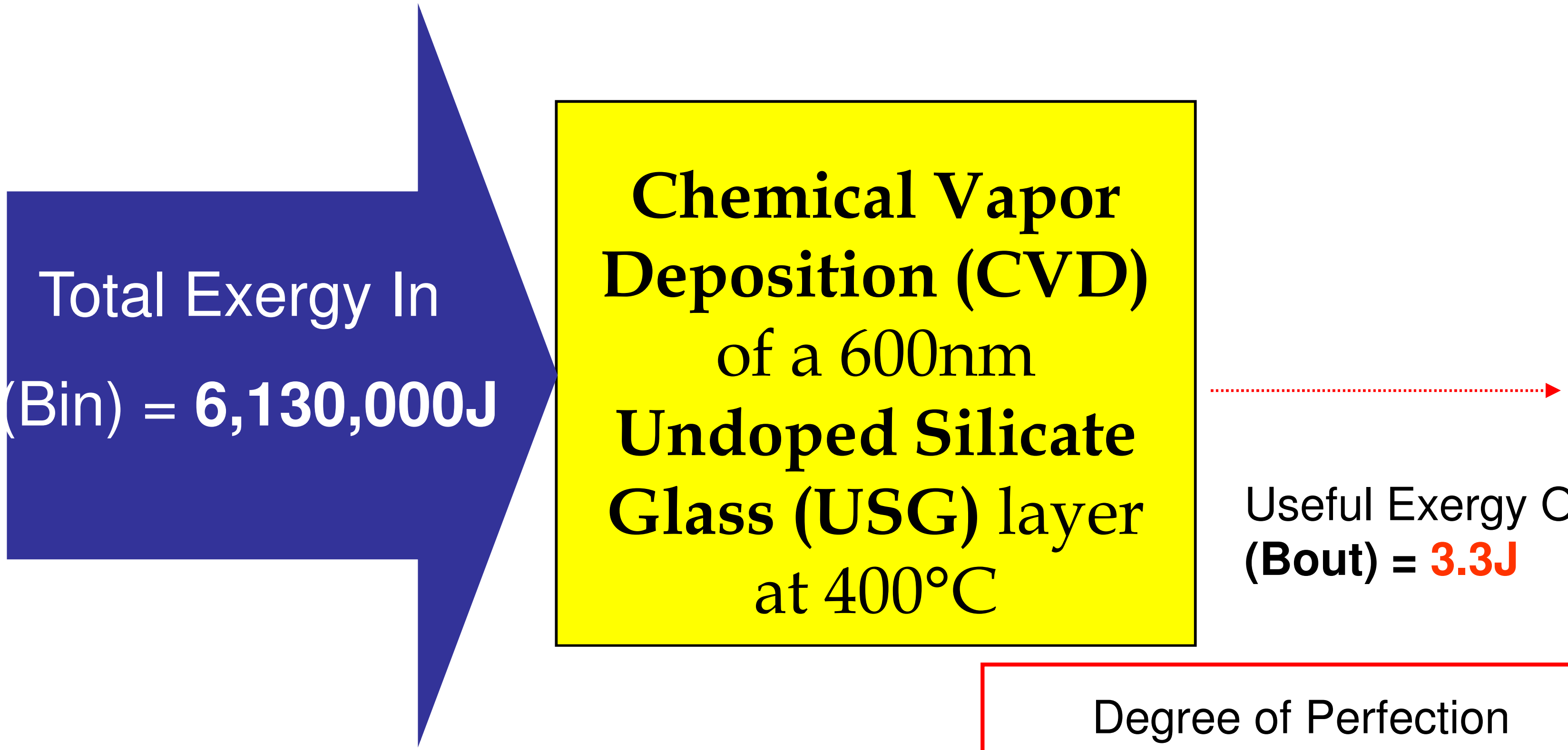
Input Energy

Electricity		2220000J	2220000	36.2

Outputs

Undoped Silicate Glass laye	0.0248	0.000414mol	3.2667	

CVD Degree of Perfection



Total Exergy In

(Bin) = **6,130,000J**

Chemical Vapor Deposition (CVD) of a 600nm **Undoped Silicate Glass (USG)** layer at 400°C

Useful Exergy Out
(Bout) = 3.3J

Component	Exergy in (J)
Input Gases	45,900
Cleaning Gases	3,865,000
Electricity*	2,220,000

*not including utility losses

Degree of Perfection

$$\eta_P = \frac{3.267J}{6{,}131{,}123J} = 5.33 * 10^{-7}$$

Data from Sarah Boyd et. al. (2006)

CVD deposition of SiO_2 glass

$SiH_4 + O_2 \rightarrow SiO_2 + H_2$

$1383.7 + 3.97 - 7.9 + 2X236.1 = 907.6$ kJ/mol SiO_2

907.6 kJ/ mol x 1 mol/60g x 1000g/kg = 15MJ/kg

Actual electricity = 2.2 MJ/0.0248 g => 88.7 GJ/kg

$\eta = 15.13/88{,}700 = 1.7 \times 10^{-4}$

Thermal Oxidation

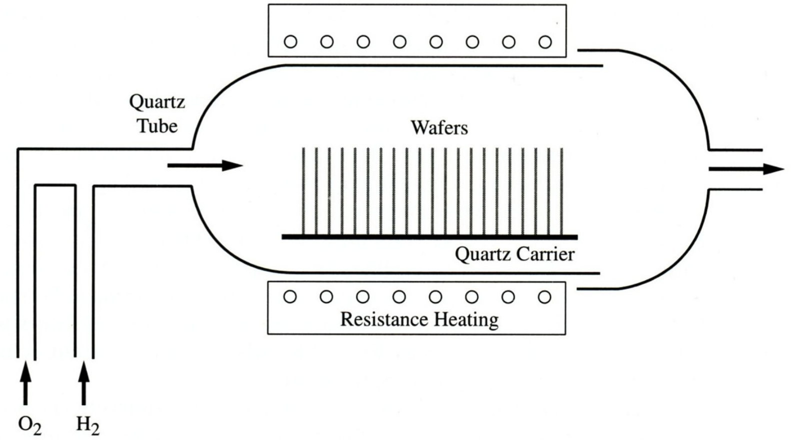


Figure 6–7 Conceptual silicon oxidation system.

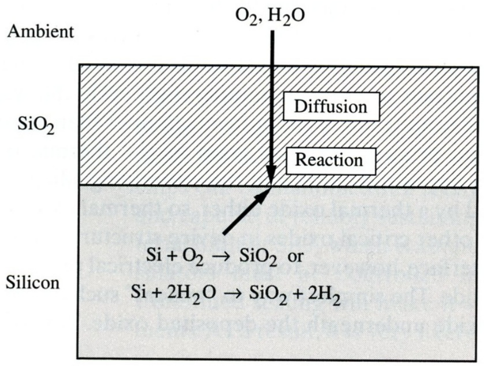


Figure 6–2 Basic process for the oxidation of silicon. The chemical reaction takes place at the Si/SiO₂ interface.

Wet Oxidation Process

Input Gases				
Species	*Input mass (g)*	*Input moles or energy (J)*	*Exergy (J)*	*%Total Input Exergy*
N2	54.069	1.9301	1331.769	0.00089
O2	6.1399	0.19188	761.7636	0.00051
H2	0.4479	0.22218	52456.7	0.0351
Silicon Consumed from Substrate				
Si	0.03091	0.001101	940.54	0.00063
Input Energy				
Electricity		149256000	149256000	0.99963

Outputs				
SiO2 layer	0.066253	0.001103	8.711	

degree of perfection

$\eta_P = 5.83*10^{-8}$

Sputtering of an AlCu film (Full Process)

Inputs	Mass (g)	Moles	Specific Chemical Exergy (kJ/mol)	Exergy (kJ)
Input Materials				
Ar	3.43	0.09	11.69	1.00
AlCu	2.44	0.09	885.0	78.96
Input Energy				
Electricity				29909
	Total In			29988
Output				
AlCu Film	0.498	1.82E-02	885.04	16.13
	Total Out			16.13
Degree of Perfection (_ $_P$)				5.38E-04

Dry Etching of a Silicon Nitride Film (Full Process)

Inputs	Mass (g)	Moles	Specific Chemical Exergy (kJ/mol)	Exergy (kJ)
Input Materials				
He	2.46E-02	6.13E-03	30.37	1.86E-01
SF_6	2.688	1.84E-02	281.8	5.2
Input Energy				
Electricity				1178
	Total In			1184
Output				
Etched Si_3N_4	0.033	2.34E-04	1917.88	0.45
	Total Out			0.45
Exergetic Efficiency of Removal (_ $_R$)				3.79E-04

Wet Etching of a Silicon Nitride Film (Etch Only)

Inputs	Mass (g)	Moles	Specific Chemical Exergy (kJ/mol)	Exergy (kJ)
Input Materials				
H_3PO_4	252.82	2.58	104.00	268.32
H_2O	72.432	4.02	0.90	3.62
Input Energy				
Electricity				525.6
	Total In			797.5
Output				
Etched Si_3N_4	0.301	2.15E-03	1917.88	4.12
	Total Out			4.12
Exergetic Efficiency of Removal (_ $_R$)				5.14E-03

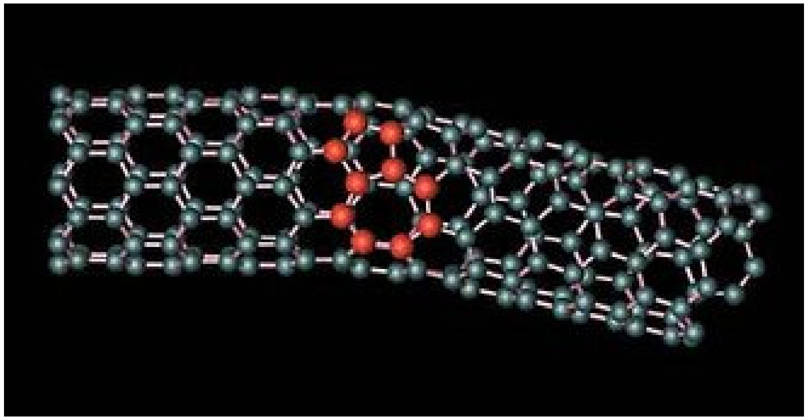
Tables from
Matthew Branham
MS thesis 2008

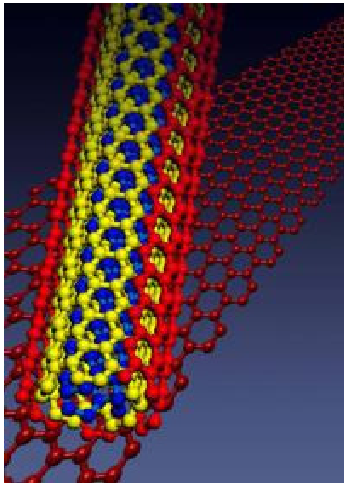
Data taken from MEMS facility

Degree of Perfection depends upon exergy of output

Note some are removal processes

Production of Carbon SWNT





Production by high pressure carbon monoxide process “HiPCO”
$2CO \rightarrow CO2 + C$ => 10 - 12 MJ/kg
Estimates of electricity inputs ~ 30 GJ/kg, η = 12/30,000 =0.04%

Summary for η_P ; η

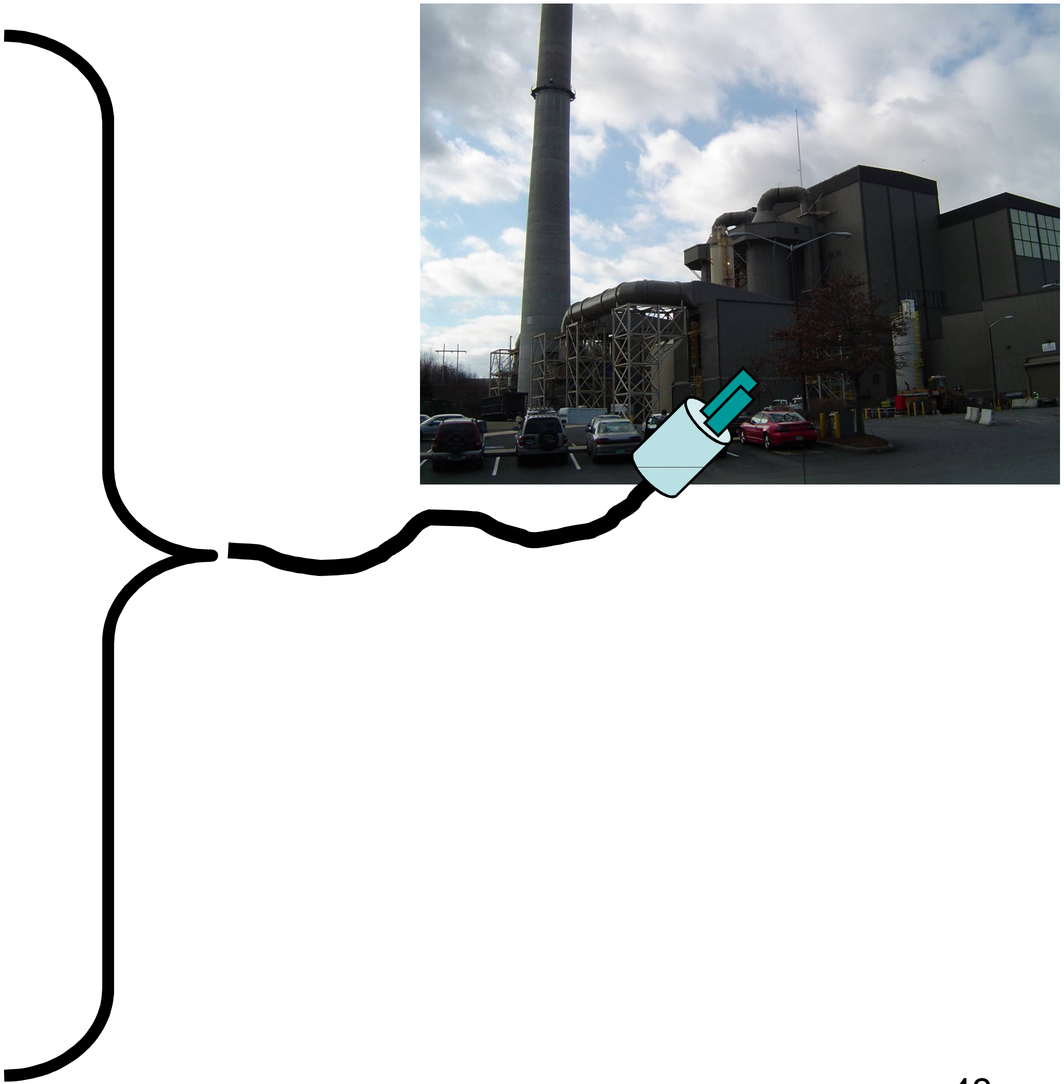
- Heating & Melting ~ 0.5; 0.5
- Machining ~ 0.05; 0.05 to 0.5 compared to u_s
- Grinding ~ 0.005
- Sputter, Wet and Dry Etching ~ 5×10^{-4}
- PECVD (SiO2) ~ 10^{-6} ; 10^{-4}
- Wet Oxidation ~ 10^{-8}; (potentially negative)
- SWCNT ~ ____; 4×10^{-4}

Comments

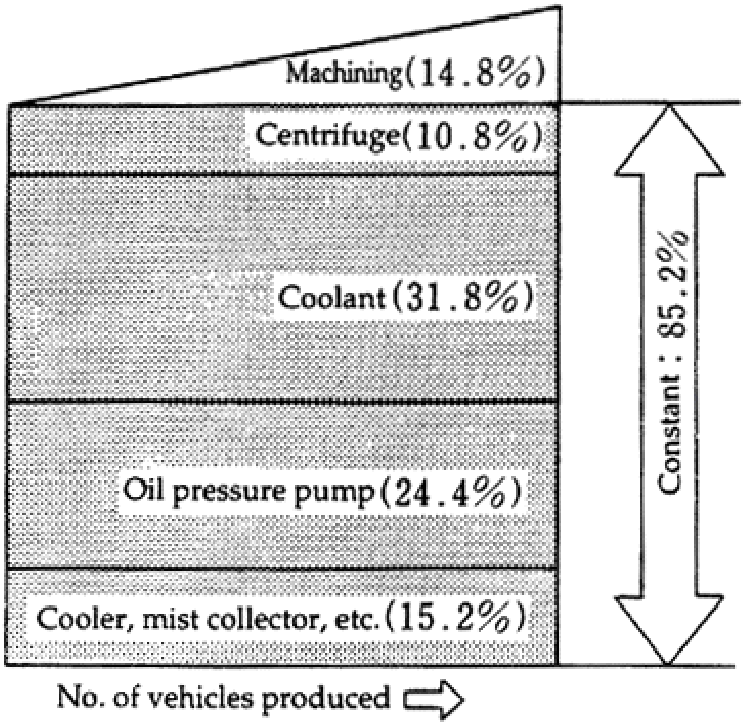
- These can be quite sensitive to rate when idle power is high
- Transit Exergy for melting processes
- Exergy of Auxiliary materials: etching, cleaning, pollution abatement, abrasive waterjet
- Also affected by exergy of the output

Energy (Electricity) Only

1. Machining
2. Grinding
3. Casting
4. Injection Molding
5. Abrasive Waterjet
6. EDM
7. Laser DMD
8. CVD
9. Sputtering
10. Thermal Oxidation

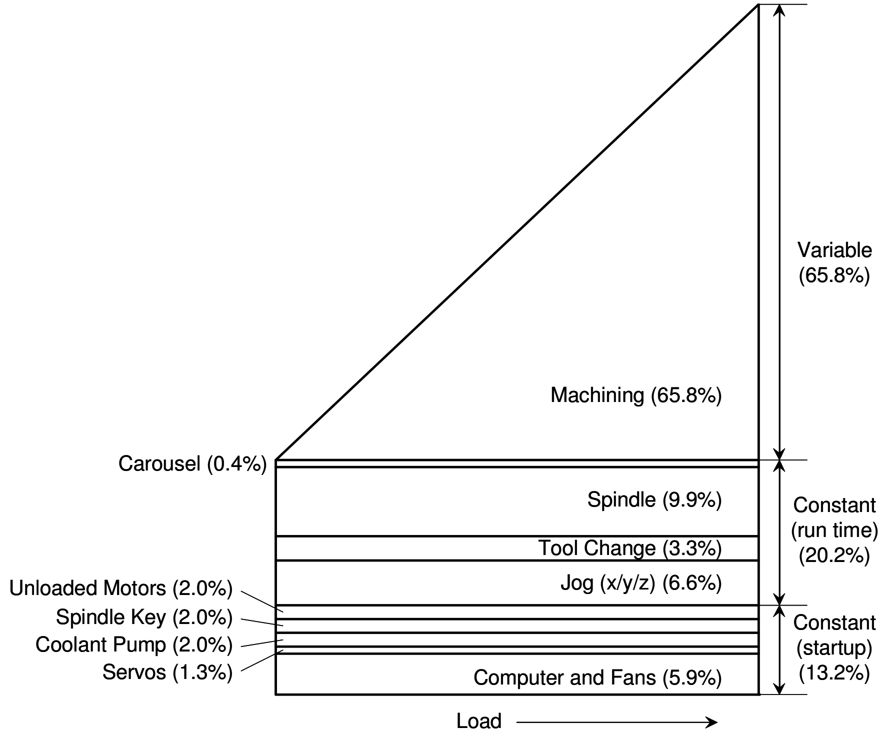


Energy Requirements at the Machine Tool



Energy Use Breakdown by Type

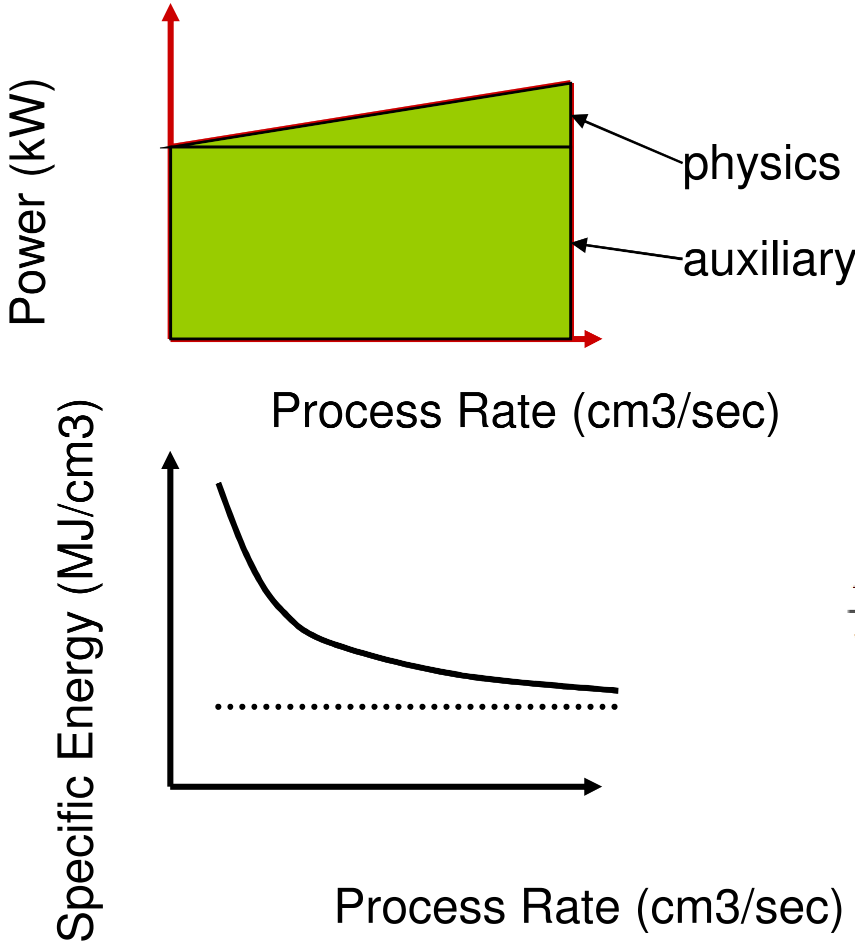
Production Machining Center



Automated Milling Machine

From Toyota 1999, and Kordonowy 2002.

Electric Energy Intensity for Manufacturing Processes



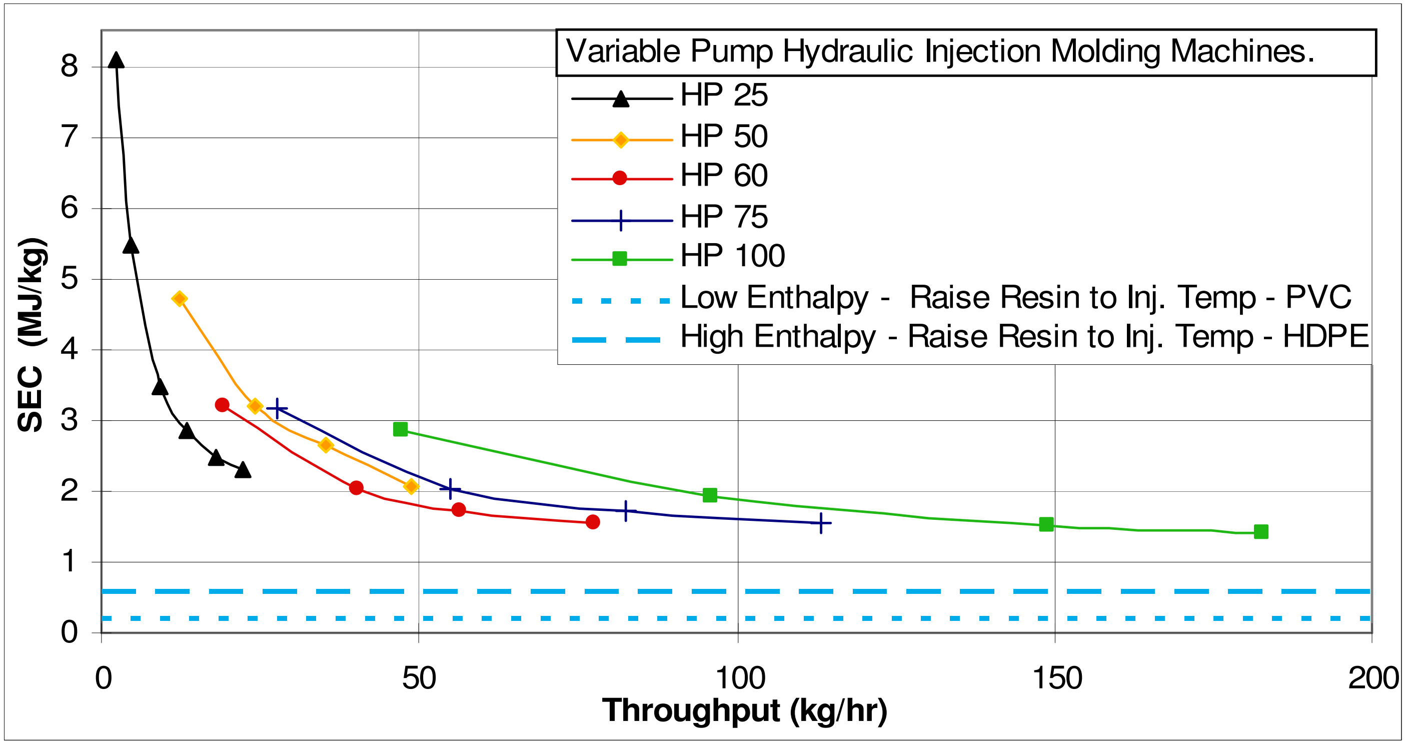
physics

auxiliary equipment & infrastructure

$$P = P_o + k_v \dot{V}_{processed}$$

$$\frac{P}{\dot{V}} = \frac{P_o}{\dot{V}} + k_v = \frac{E}{V}$$

Injection Molding Machines



Source: [Thiriez '06]

$$\frac{P}{\dot{m}} = \frac{P_o}{\dot{m}} + k_m = \frac{E}{m}$$

Does not account for the electric grid.

Thermal Oxidation, SiO_2

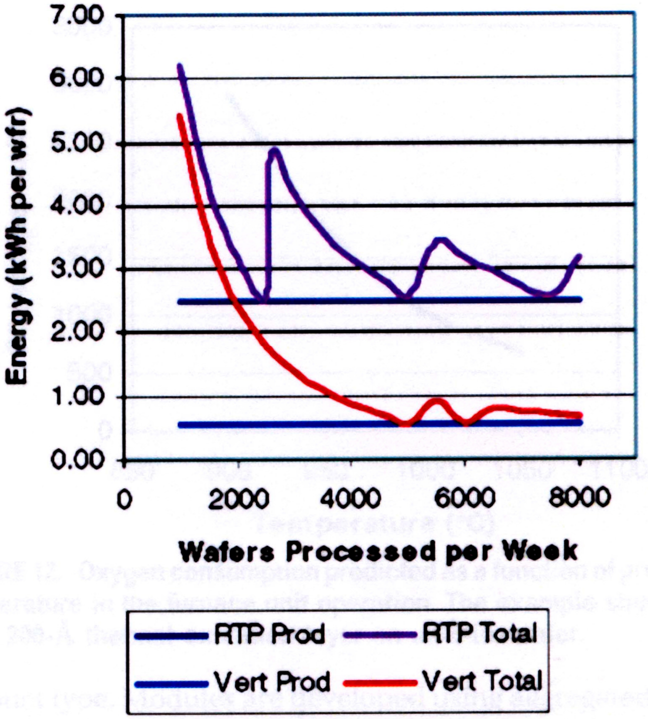


FIGURE 9. Energy consumption for growth of a 25-Å oxide layer as a function of equipment type (RTP vs vertical furnace), number of wafers processed per week, and total run time (production plus idle). The example shown is for 8-in. wafers.

Ref: Murphy et al
es&t 2003

Power Requirements

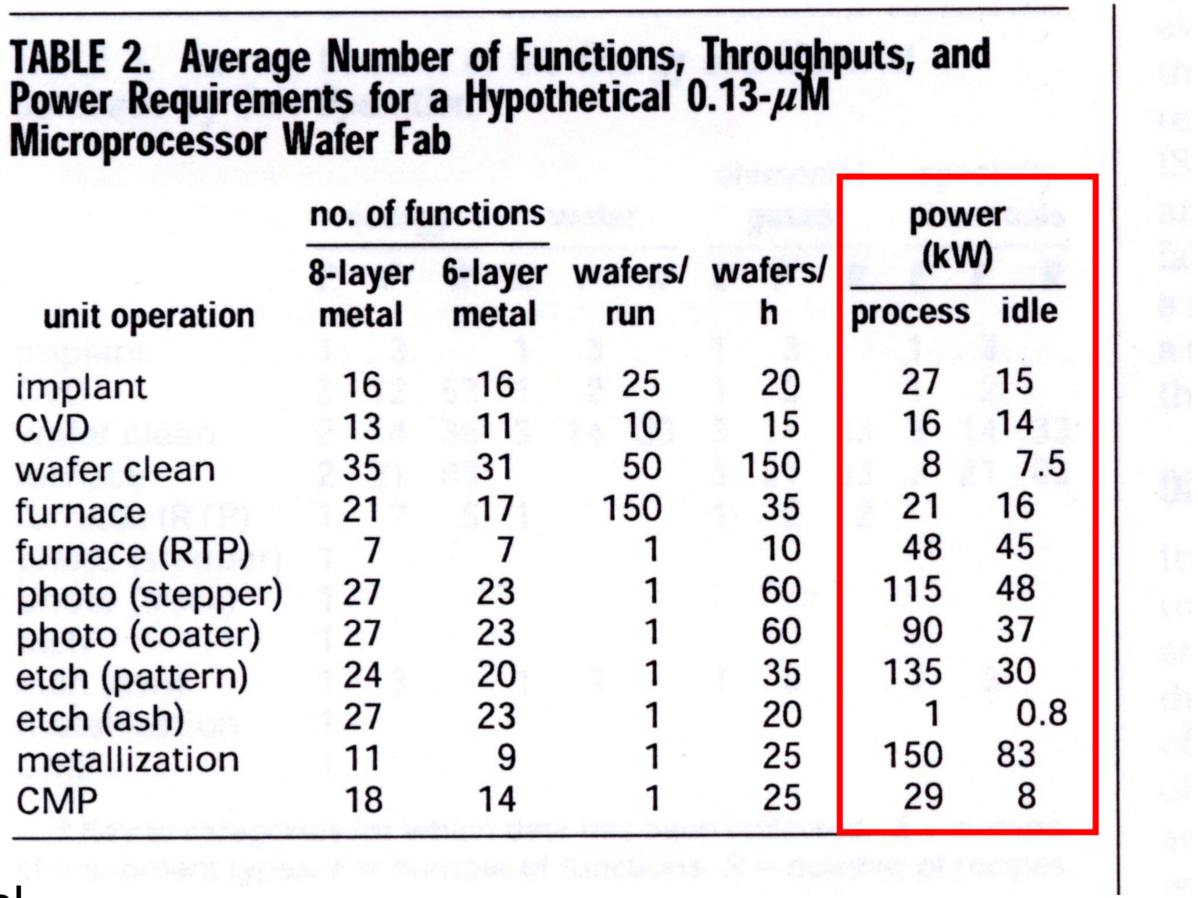


TABLE 2. Average Number of Functions, Throughputs, and Power Requirements for a Hypothetical 0.13-μM Microprocessor Wafer Fab

unit operation	no. of functions 8-layer metal	6-layer metal	wafers/run	wafers/h	power (kW) process	idle
implant	16	16	25	20	27	15
CVD	13	11	10	15	16	14
wafer clean	35	31	50	150	8	7.5
furnace	21	17	150	35	21	16
furnace (RTP)	7	7	1	10	48	45
photo (stepper)	27	23	1	60	115	48
photo (coater)	27	23	1	60	90	37
etch (pattern)	24	20	1	35	135	30
etch (ash)	27	23	1	20	1	0.8
metallization	11	9	1	25	150	83
CMP	18	14	1	25	29	8

Ref: Murphy et al
es&t 2003

Process Name	Power Required	Process Rate		Electricity Required	References
	kW	cm^3/s		J/cm^3	
Injection Molding	10.76 - 71.40	3.76 - 50.45	of polymer processed	1.75E+03 - 3.41E+03	[Thiriez 2006]
Machining	2.80 - 194.80	0.35 - 20.00	of material removed	3.50E+03 - 1.87E+05	[Dahmus 2004], [Morrow, Qi & Skerlos 2004] & [Time Estimation Booklet 1996]
Finish Machining	9.59	2.05E-03	of material removed	4.68E+06	[Morrow, Qi & Skerlos 2004] & [Time Estimation Booklet 1996]
CVD	14.78 - 25.00	6.54E-05 - 3.24E-03	of material deposited on wafer area	4.63E+06 - 2.44E+08	[Murphy et al. 2003], [Wolf & Tauber 1986, p.170], [Novellus Concept One 1995b] & [Krishnan Communication 2005]
Sputtering	5.04 - 19.50	1.05E-05 - 6.70E-04	of material deposited on wafer area	7.52E+06 - 6.45E+08	[Wolf & Tauber 1986] & [Holland Interview]
Grinding	7.50 - 0.03	1.66E-02 - 2.85E-02	of material removed	6.92E+04 - 3.08E+05	[Baniszewski 2005] & [Chryssolouris 1991]
Waterjet	8.16 - 16.00	5.15E-03 - 8.01E-02	of material removed	2.06E+05 - 3.66E+06	[Kurd 2004]
Wire EDM	6.60 - 14.25	2.23E-03 - 2.71E-03	of material removed	2.44E+06 - 6.39E+06	[Sodick], [Kalpakjian & Schmid 2001], & [AccuteX 2005]
Drill EDM	2.63	1.70E-07	of material removed	1.54E+10	[King Edm 2005] & [McGeough, J.A. 1988]
Laser DMD	80.00	1.28E-03	of material removed	6.24E+07	[Morrow, Qi & Skerlos 2004]
Thermal Oxidation	21.00 - 48.00	4.36E-07 - 8.18E-07	of material deposited on wafer area	2.57E+10 - 1.10E+11	[Murphy et al. 2003]

In General, over many manufacturing processes,

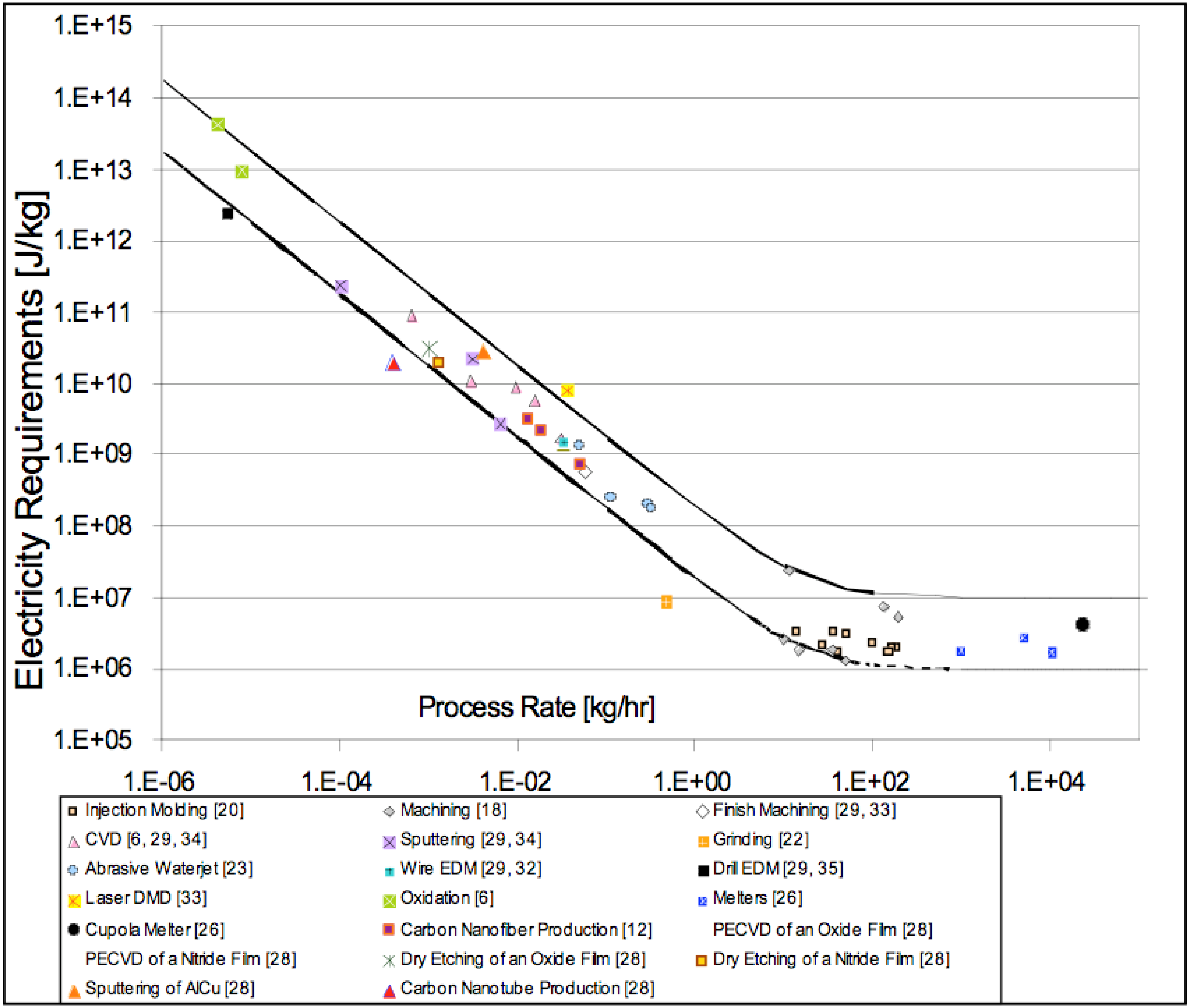
Idle Power

$$5kW \le P_o \le 50kW$$

and

Material Process Rates

$$10^{-7}\ \mathrm{cm}^3/\mathrm{sec} \le \dot{V} \le 1\ \mathrm{cm}^3/\mathrm{sec}$$



1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
Electricity Requirements [J/kg]
Process Rate [kg/hr]
1.E-06
1.E-04
1.E-02
1.E+00
1.E+02
1.E+04
Injection Molding [20]
Machining [18]
Finish Machining [29, 33]
CVD [6, 29, 34]
Sputtering [29, 34]
Grinding [22]
Abrasive Waterjet [23]
Wire EDM [29, 32]
Drill EDM [29, 35]
Laser DMD [33]
Oxidation [6]
Melters [26]
Cupola Melter [26]
Carbon Nanofiber Production [12]
PECVD of an Oxide Film [28]
PECVD of a Nitride Film [28]
Dry Etching of an Oxide Film [28]
Dry Etching of a Nitride Film [28]
Sputtering of AlCu [28]
Carbon Nanotube Production [28]

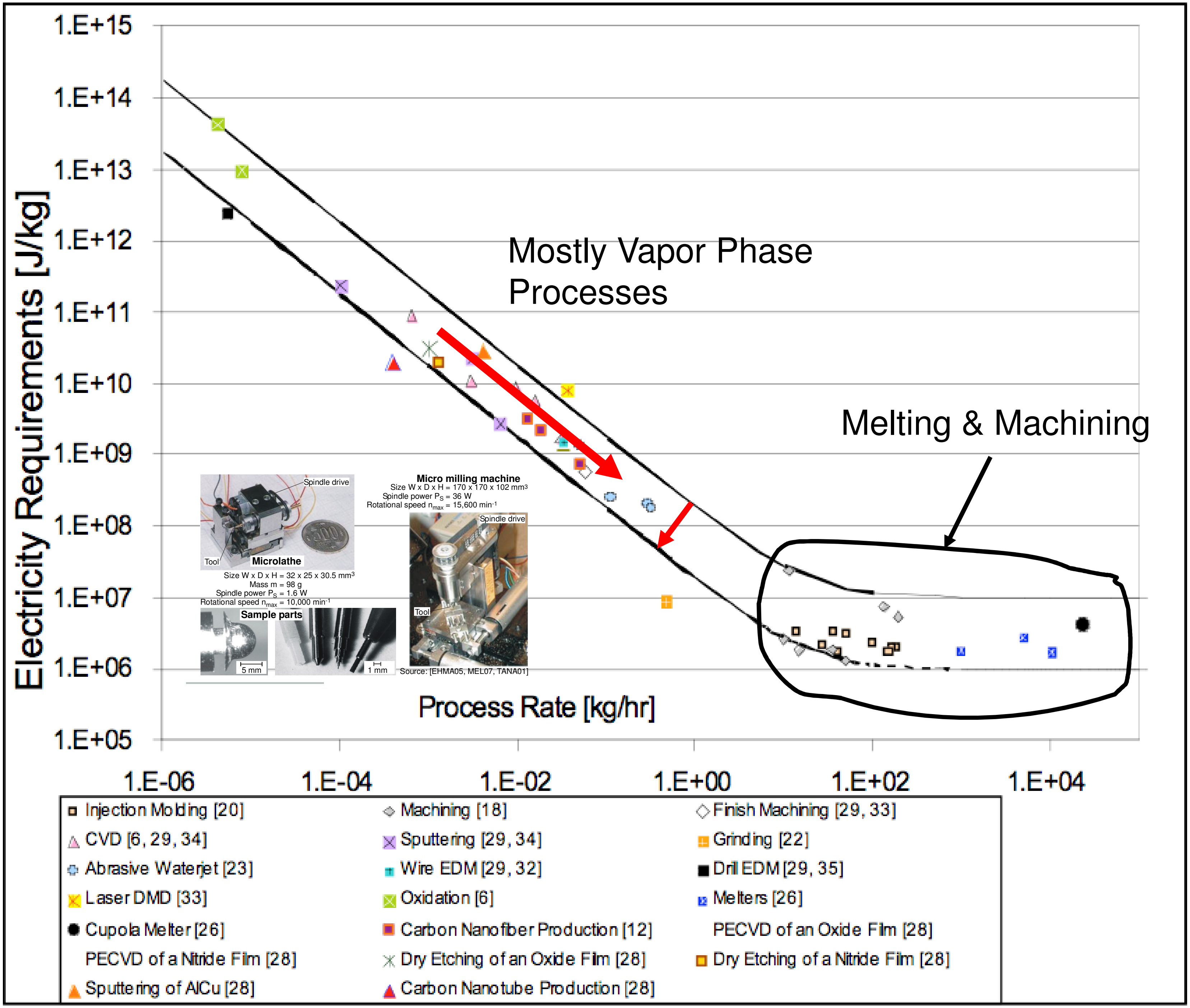
Why are these energy intensities so high?

- demand for small devices, prices for energy & materials stable/declining
- vapor phase processes with slow deposition rates
- efficiency used to enhance performance, not to downsize equipment
- However, the trajectory of individual processes is usually toward faster rates and lower energy intensities

Keep in Mind

- This is intensity not total used
- This is at the process, not cumulative exergy!
  - loses at energy conversion not included
  - investment into materials not included
  - infrastructure not included

How to Improve energy performance of mfg processes



Source: [EHMA05, MEL07, TANA01]

Improve process rate

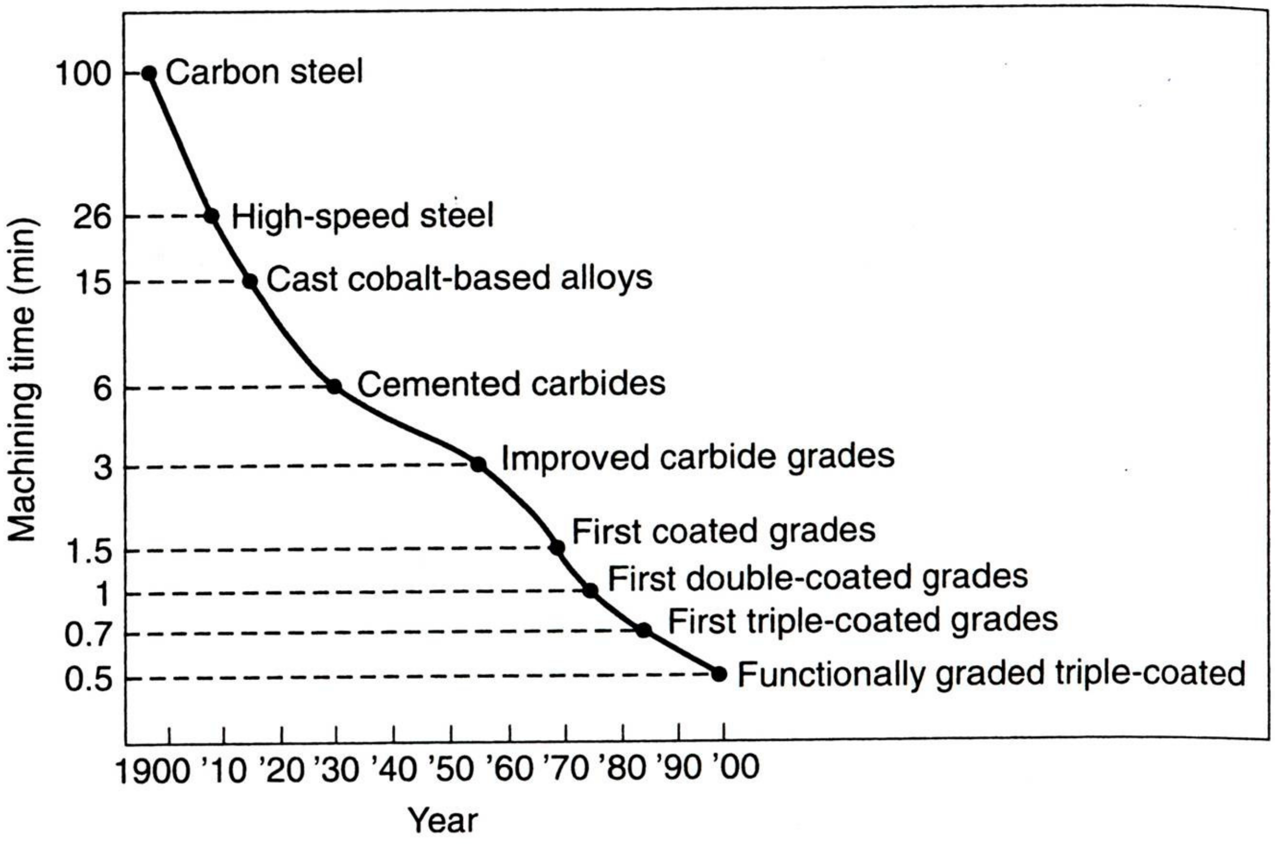
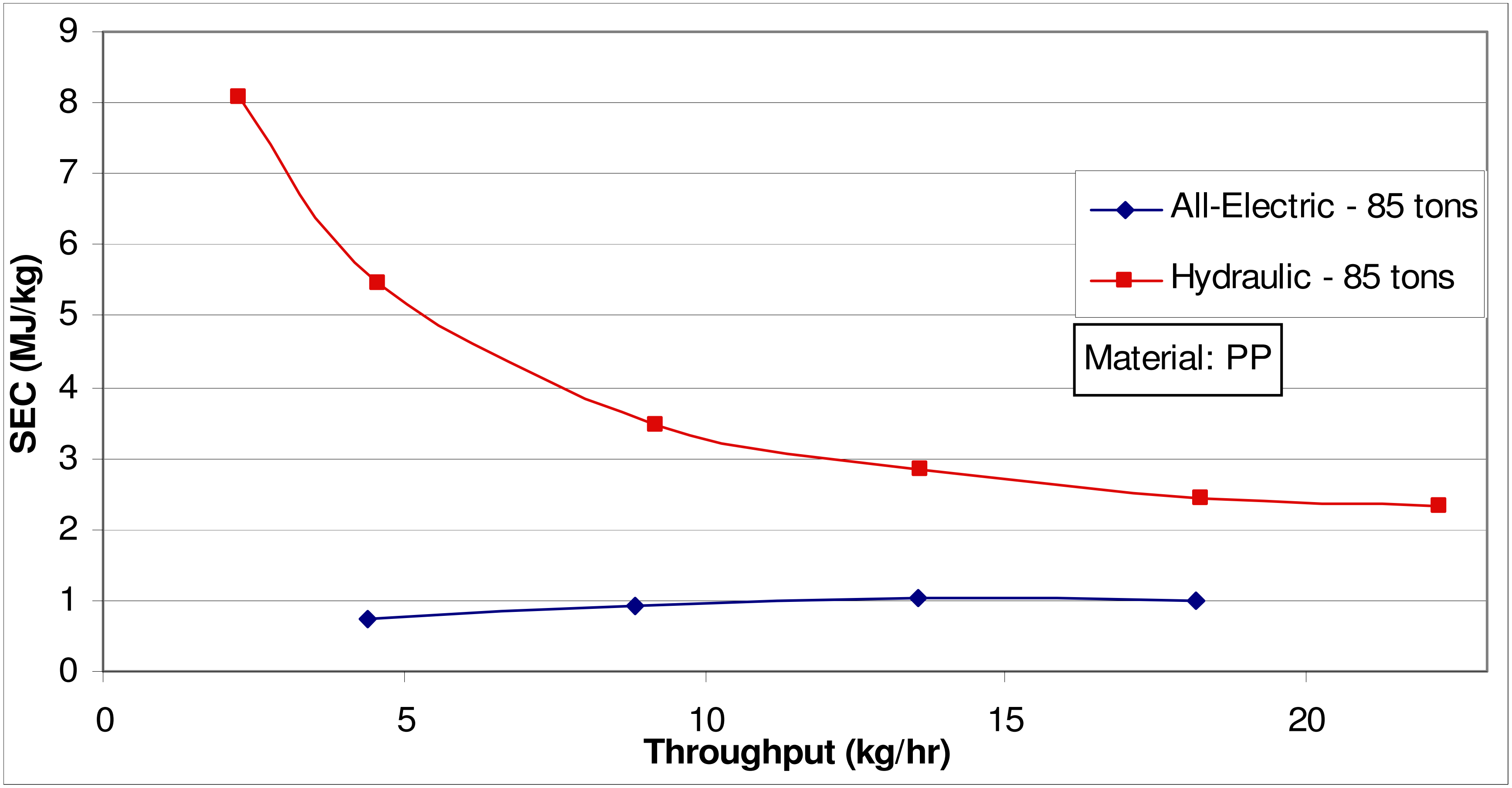


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced. Note that machining time has been reduced by two orders of magnitude within a hundred years. *Source:* Courtesy of Sandvik.

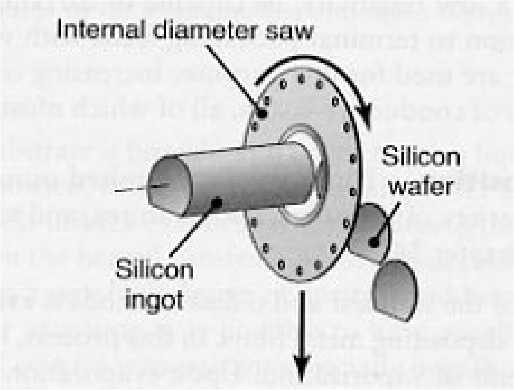
Kalpakjian

Turn un-needed equipment off

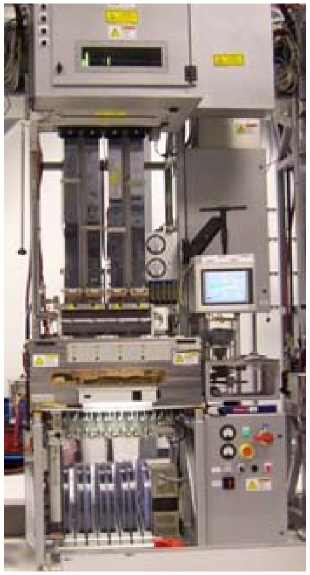


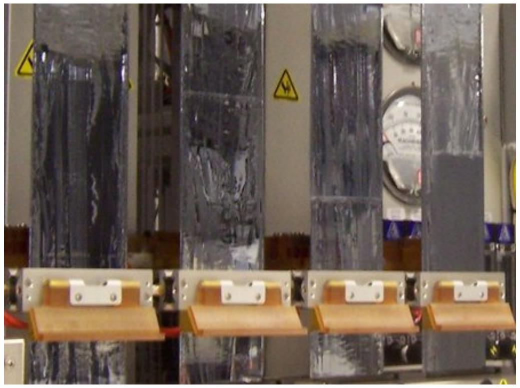
Source: [Thiriez 2006]

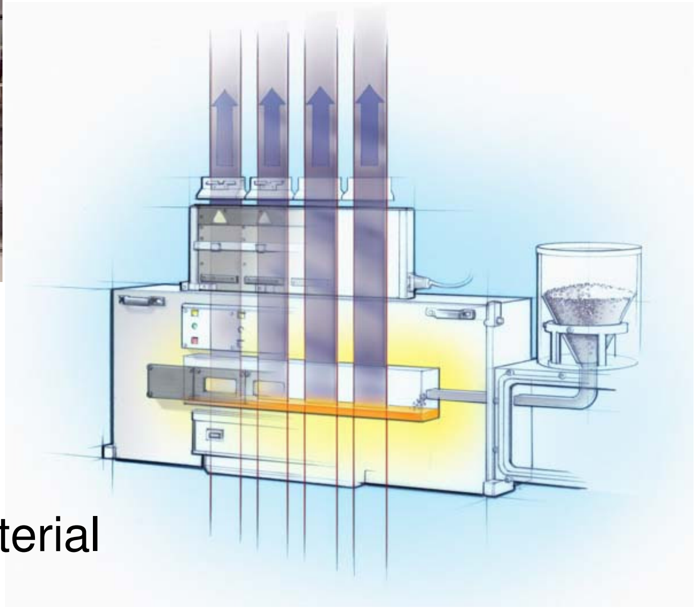
Use Less Materials



In ID and wire sawing of Si ingots, the kerf material represents lost exergy







String-Ribbon
Invented by
Ely Sachs
saves this material

Change Basic Mechanism

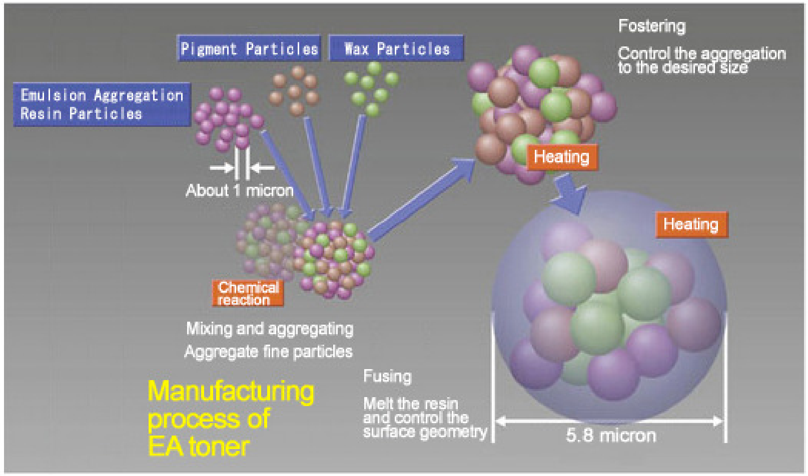
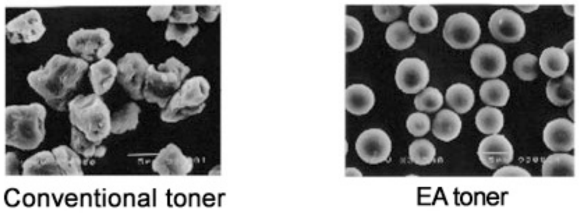


Fig. 1: Manufacturing process of EA toner


Conventional toner

EA toner

Fig. 2: Electron microscopic images of toner produced by pulverized conventional toner and EA toner

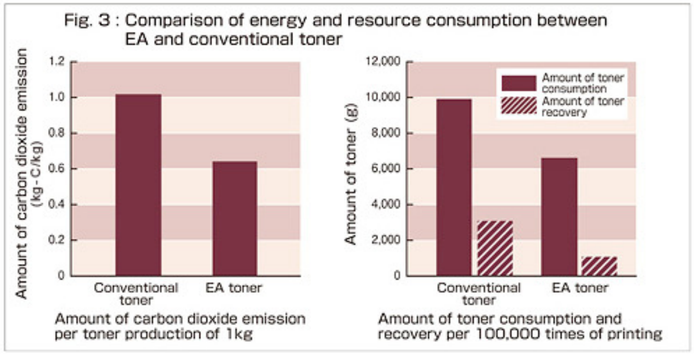
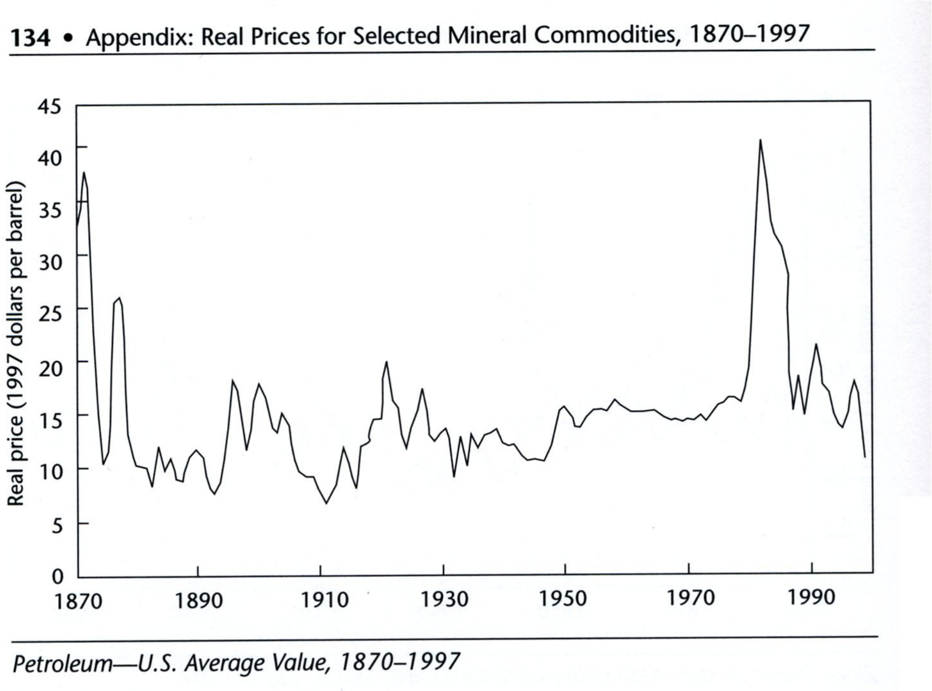


Fig. 3 : Comparison of energy and resource consumption between EA and conventional toner

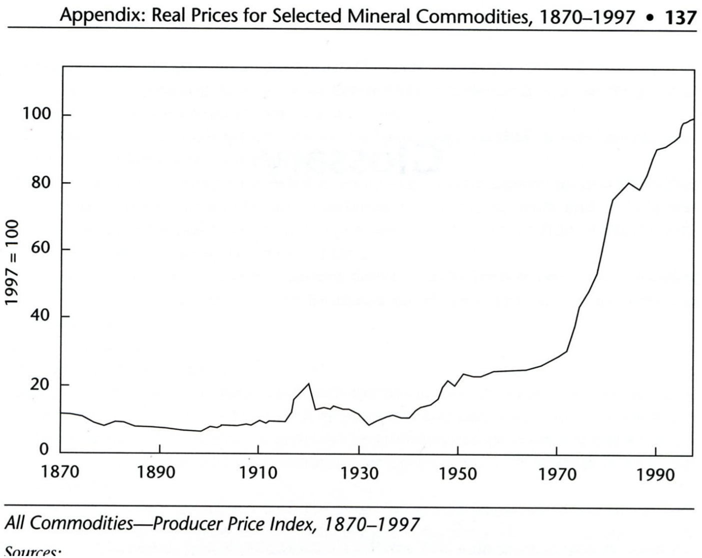
Xerox goes from grinding to emulsion polymerization
To produce toner particles

Increase the cost of energy!



134 • Appendix: Real Prices for Selected Mineral Commodities, 1870–1997

Petroleum—U.S. Average Value, 1870–1997



Appendix: Real Prices for Selected Mineral Commodities, 1870–1997 • **137**

All Commodities—Producer Price Index, 1870–1997

Sources:

SWNT cost ~ $200/g (less for larger quantities)
Electricity ~ 30MJ/g = 8.3 kWh
In Massachusetts @ 0.14/kWh = $1.17