GCEP – Stanford
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Energy & Exergy Efficiency of Manufacturing Processes

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Mfg Processes in Thermodynamic Framework

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

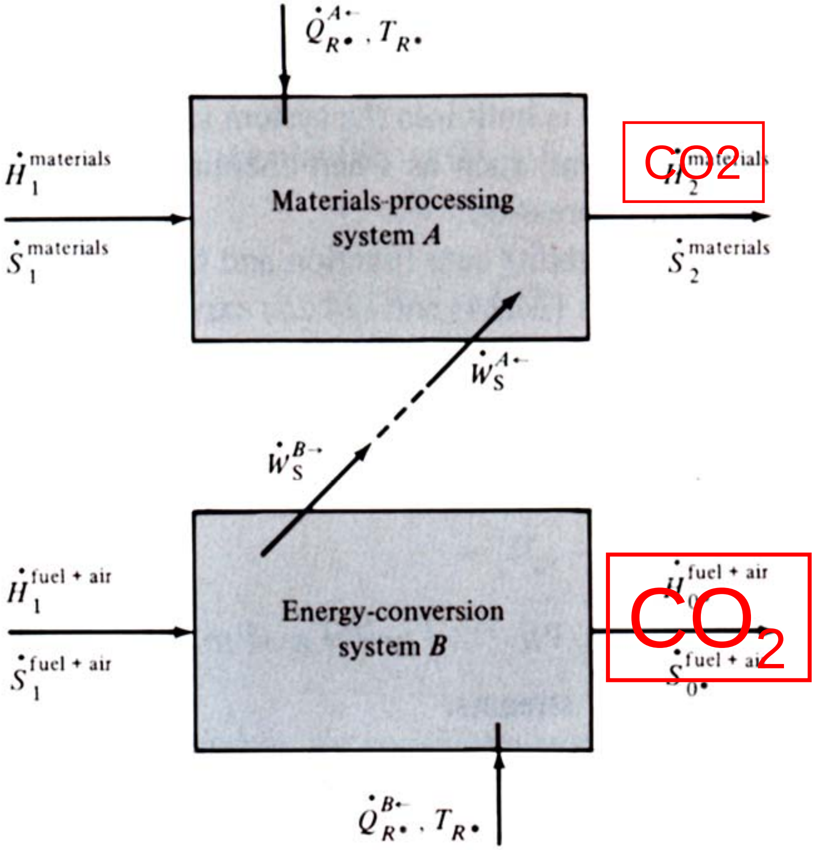

Figure from Gyftopoulos & Berreta

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Issues

1. Resource Accounting
    - Work, heat, materials transformations
2. Process Improvement
    - Minimum work or reversible work: exergy

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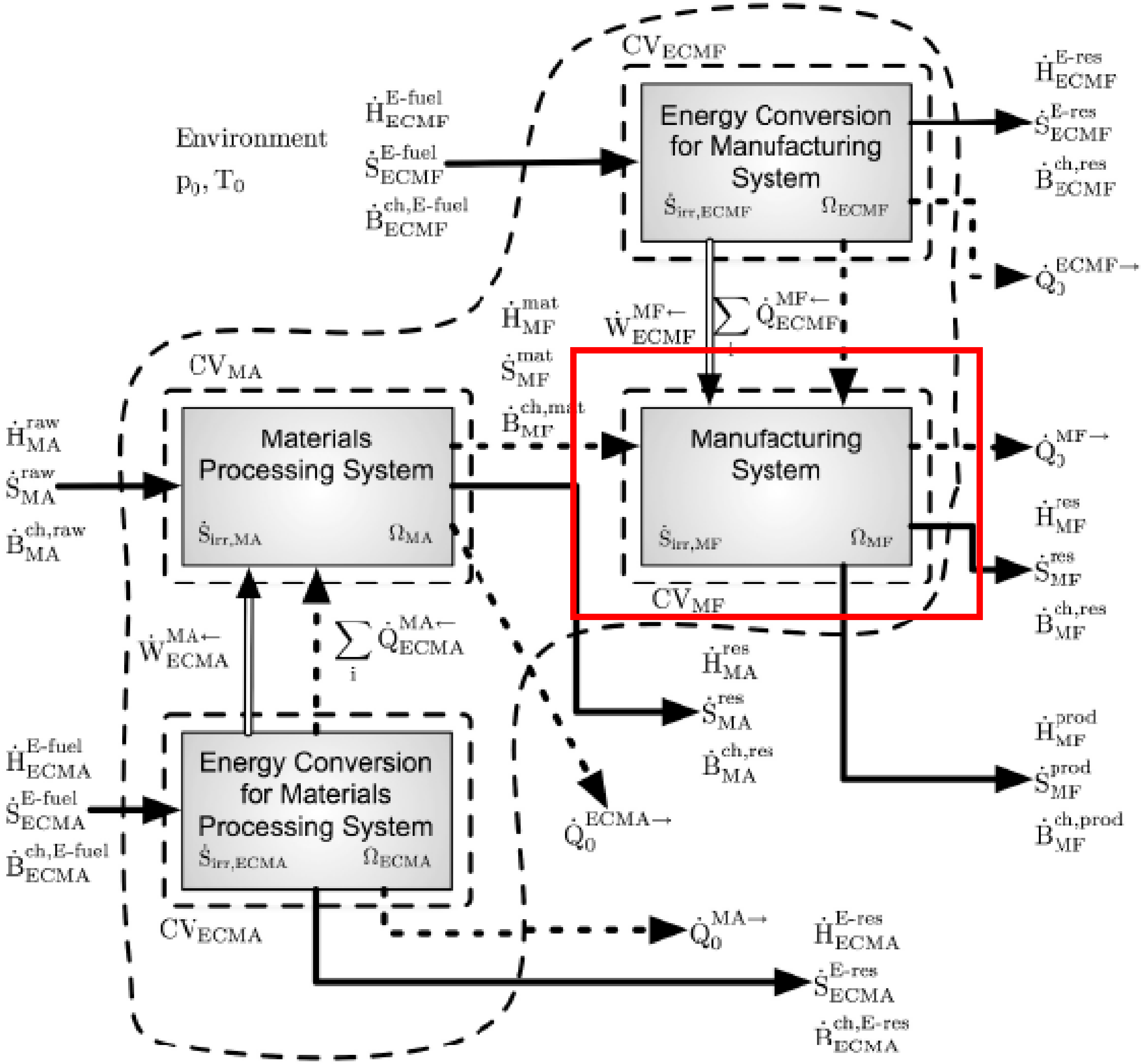
Environment
p_0, T_0
CV_{ECMF}
$\dot{H}_{ECMF}^{E\text{-fuel}}$
$\dot{S}_{ECMF}^{E\text{-fuel}}$
$\dot{B}_{ECMF}^{ch,E\text{-fuel}}$
Energy Conversion for Manufacturing System
$\dot{S}_{irr,ECMF}$
Ω_{ECMF}
$\dot{H}_{ECMF}^{E\text{-res}}$
$\dot{S}_{ECMF}^{E\text{-res}}$
$\dot{B}_{ECMF}^{ch,res}$
$\dot{Q}_0^{ECMF\rightarrow}$
$\dot{W}_{ECMF}^{MF\leftarrow}$
$\sum_i \dot{Q}_{ECMF}^{MF\leftarrow}$
$\dot{H}_{MF}^{mat}$
$\dot{S}_{MF}^{mat}$
$\dot{B}_{MF}^{ch,mat}$
CV_{MA}
$\dot{H}_{MA}^{raw}$
$\dot{S}_{MA}^{raw}$
$\dot{B}_{MA}^{ch,raw}$
Materials Processing System
$\dot{S}_{irr,MA}$
Ω_{MA}
Manufacturing System
$\dot{S}_{irr,MF}$
Ω_{MF}
CV_{MF}
$\dot{Q}_0^{MF\rightarrow}$
$\dot{H}_{MF}^{res}$
$\dot{S}_{MF}^{res}$
$\dot{B}_{MF}^{ch,res}$
$\dot{W}_{ECMA}^{MA\leftarrow}$
$\sum_i \dot{Q}_{ECMA}^{MA\leftarrow}$
$\dot{H}_{MA}^{res}$
$\dot{S}_{MA}^{res}$
$\dot{B}_{MA}^{ch,res}$
$\dot{H}_{MF}^{prod}$
$\dot{S}_{MF}^{prod}$
$\dot{B}_{MF}^{ch,prod}$
$\dot{H}_{ECMA}^{E\text{-fuel}}$
$\dot{S}_{ECMA}^{E\text{-fuel}}$
$\dot{B}_{ECMA}^{ch,E\text{-fuel}}$
Energy Conversion for Materials Processing System
$\dot{S}_{irr,ECMA}$
Ω_{ECMA}
$\dot{Q}_0^{ECMA\rightarrow}$
CV_{ECMA}
$\dot{Q}_0^{MA\rightarrow}$
$\dot{H}_{ECMA}^{E\text{-res}}$
$\dot{S}_{ECMA}^{E\text{-res}}$
$\dot{B}_{ECMA}^{ch,E\text{-res}}$

Balances for Mfg Process

Mass

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

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

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

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Work Rate for Mfg Process in Steady State

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

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

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

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Exergy and Work

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

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

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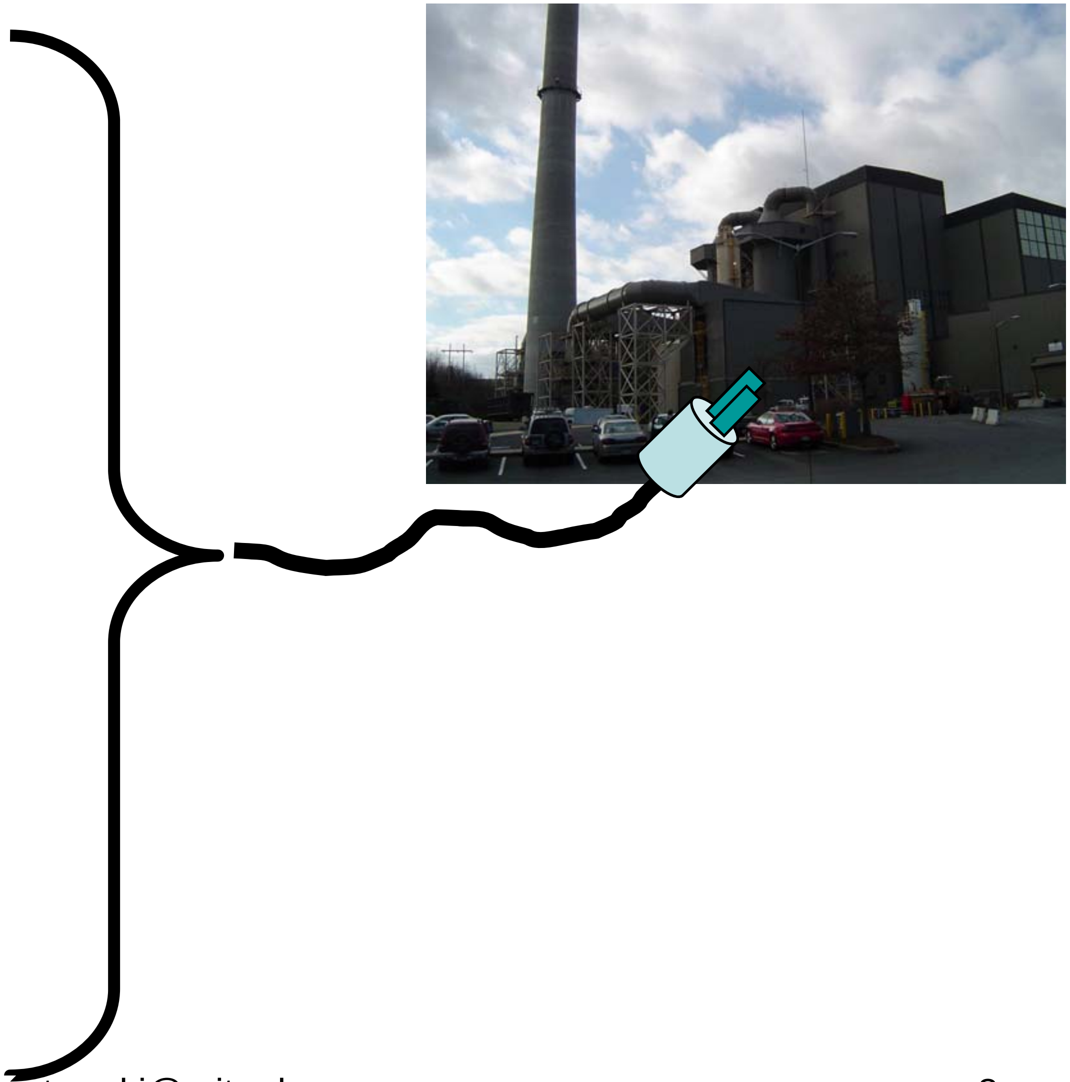
Mfg Process Use of Electricity



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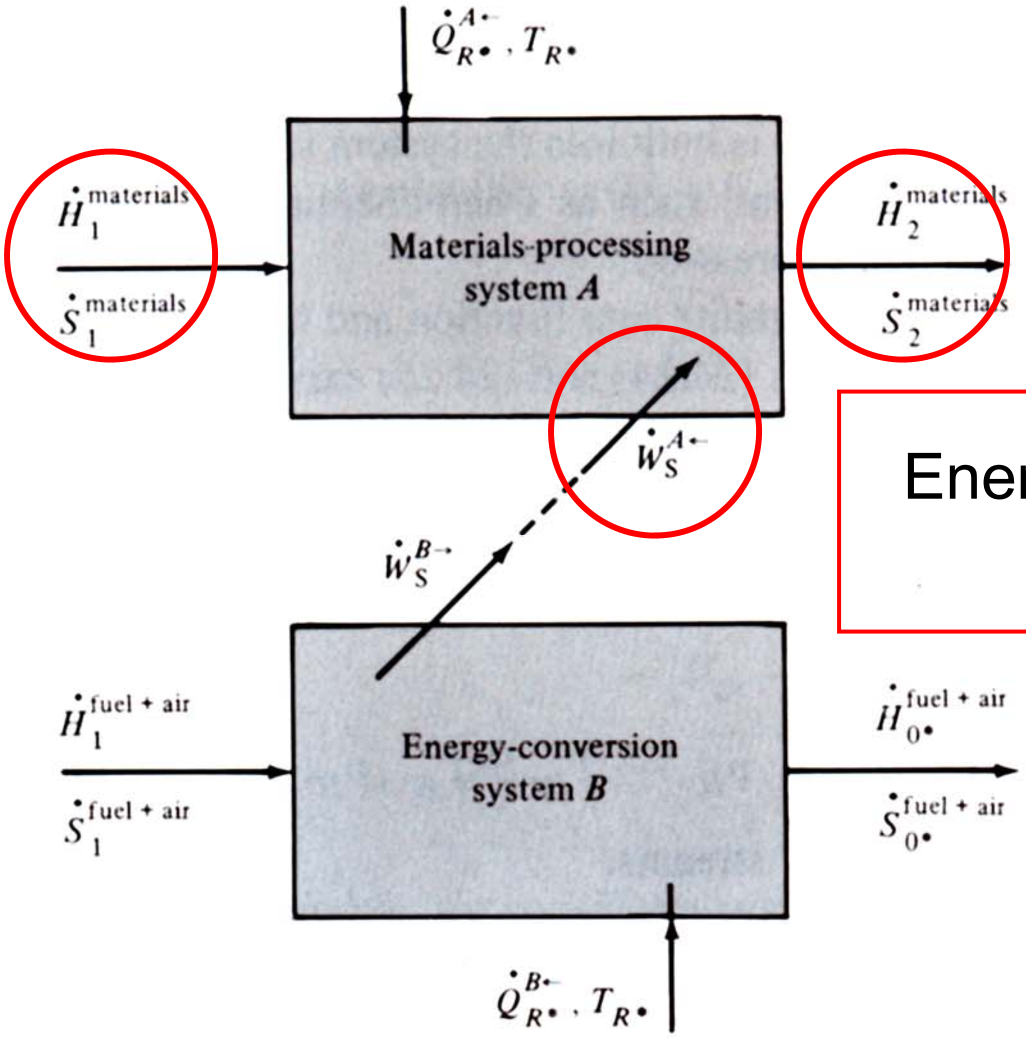
408 **Availability Functions**

Figure from Gyftopoulos & Berreta



Energy Intensity (MJ/kg)

Figure 24.2 The burning of a fuel-air mixture in the energy-conversion system provides the work needed to process the bulk-flow stream through the materials-processing system.

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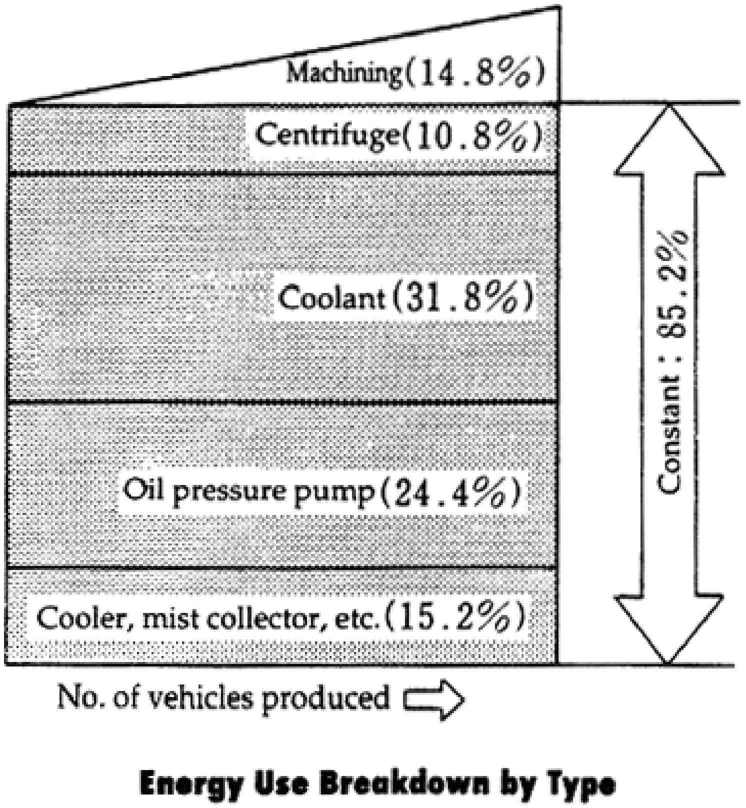
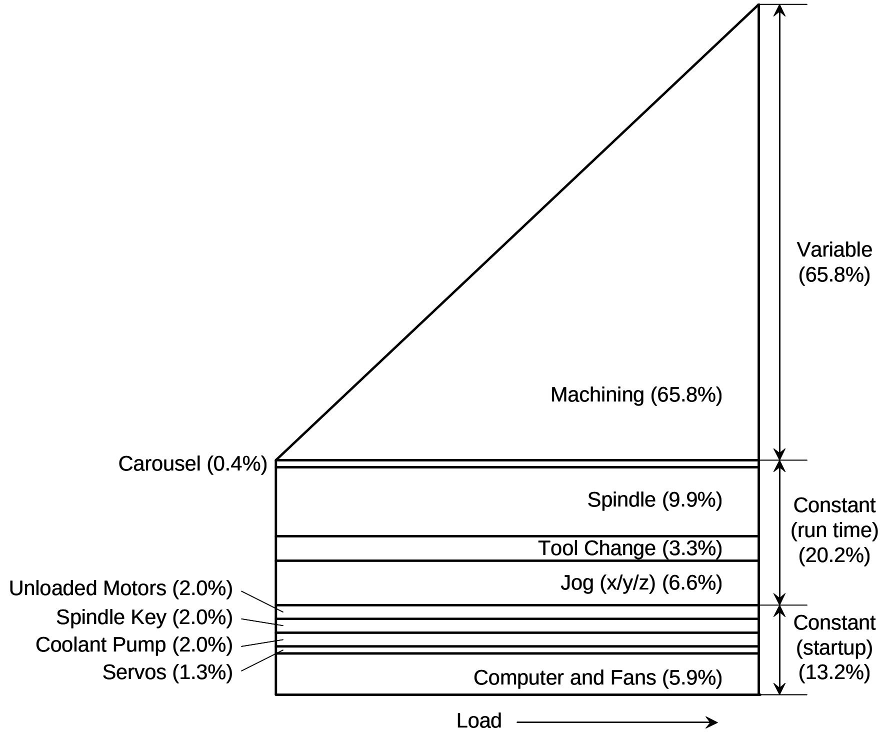
Energy Requirements at the Machine Tool



Energy Use Breakdown by Type

Production Machining Center



Automated Milling Machine

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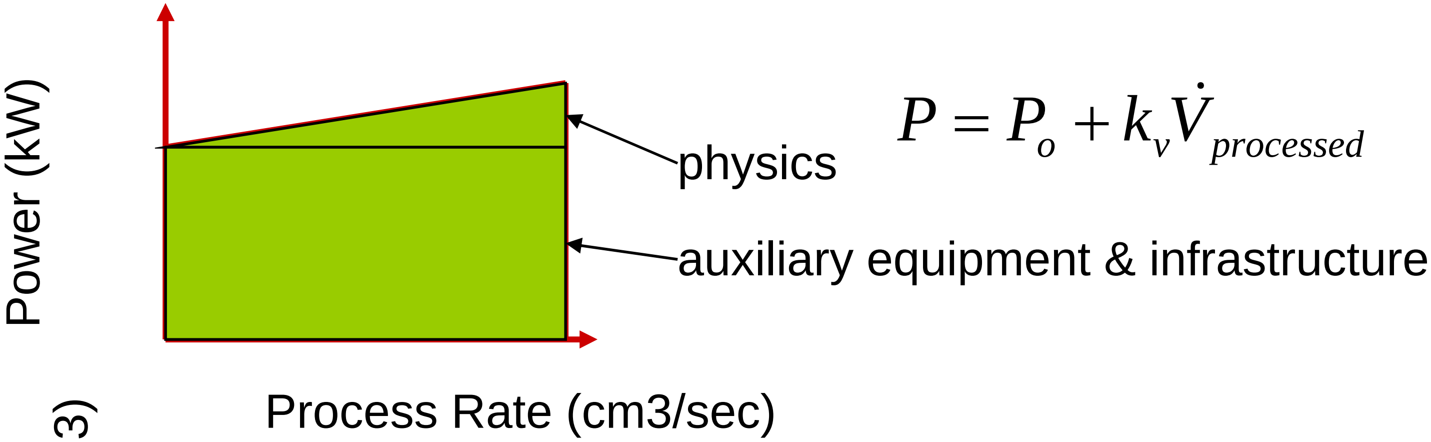
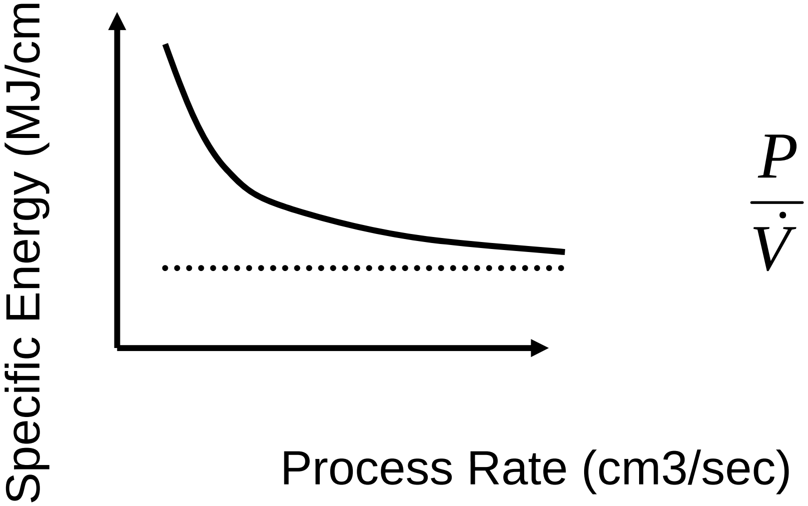
From Toyota 1999, and Kordonowy 2002.

Electric Energy Intensity for Manufacturing Processes



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



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

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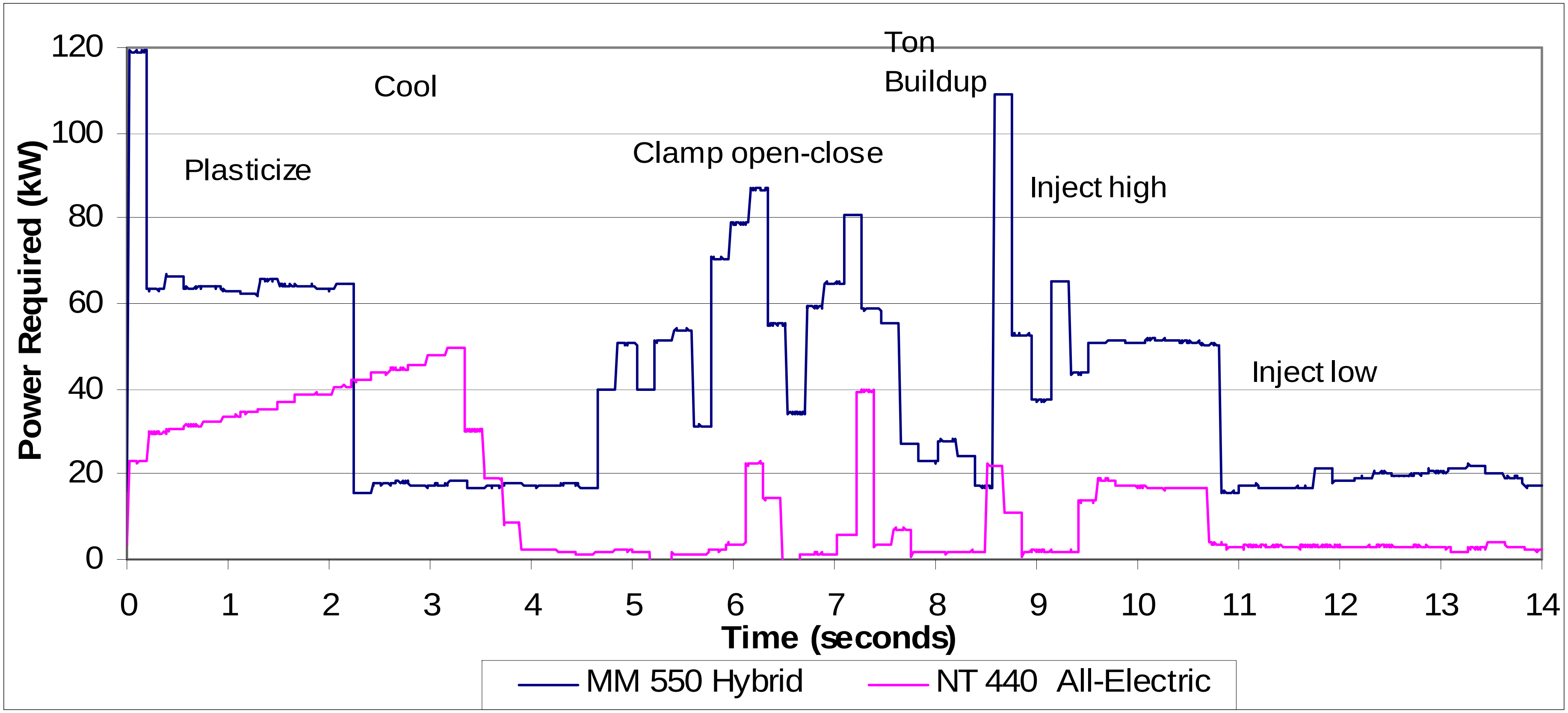
All-electric vs. hybrid



Source: [Thiriez]

The hydraulic machine would be even higher than the hybrid curve

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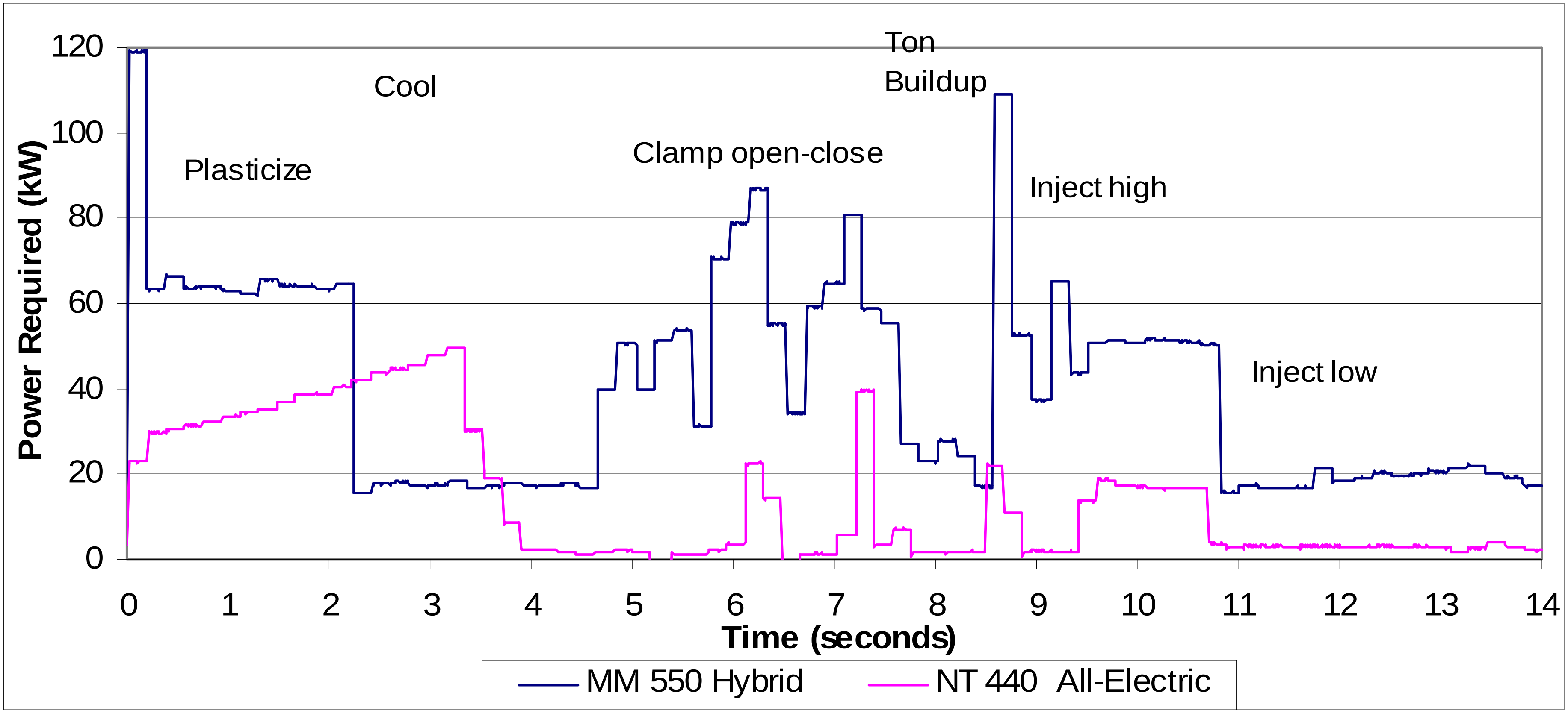
All-electric vs. hybrid



Source: [Thiriez]

The hydraulic plot would be even higher than the hybrid curve

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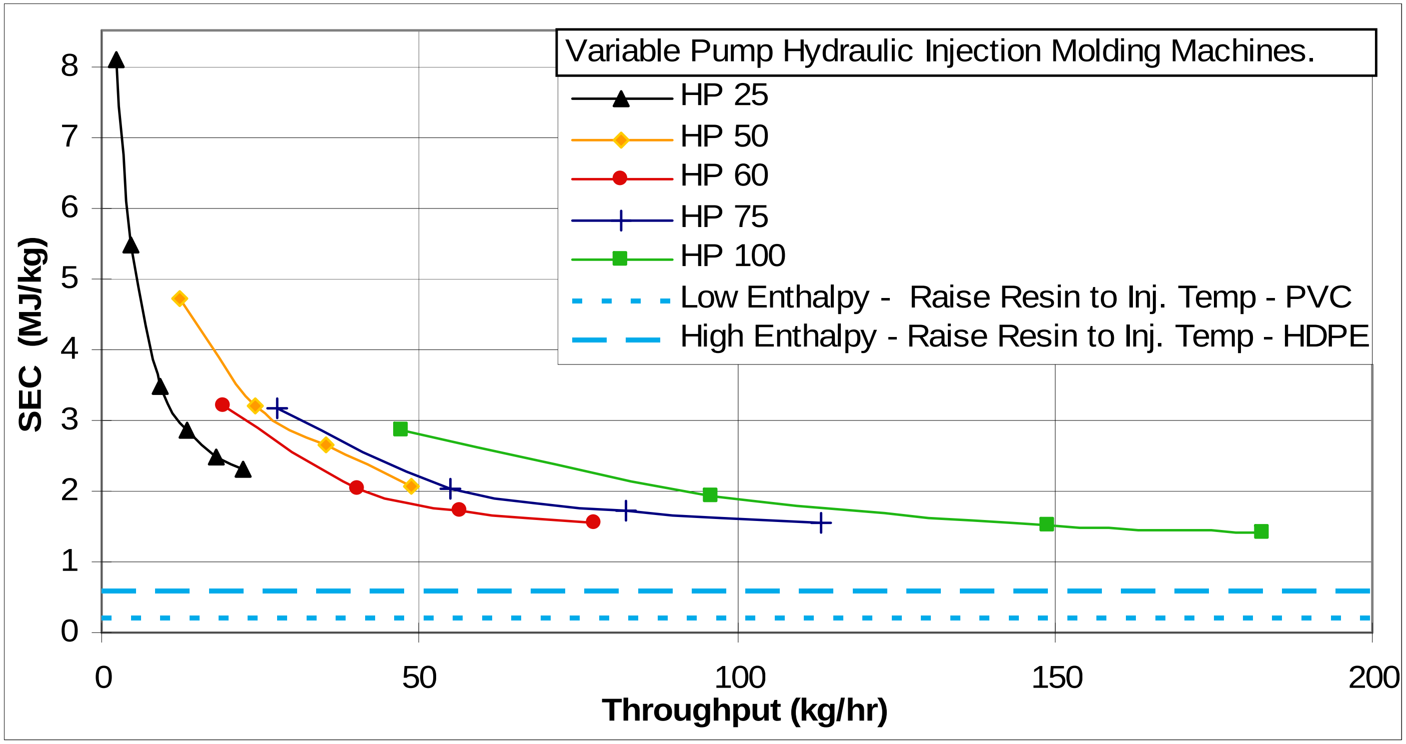
Injection Molding Machines



Source: [Thiriez '06]

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

Does not account for the electric grid.

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Thermal Oxidation, SiO_2

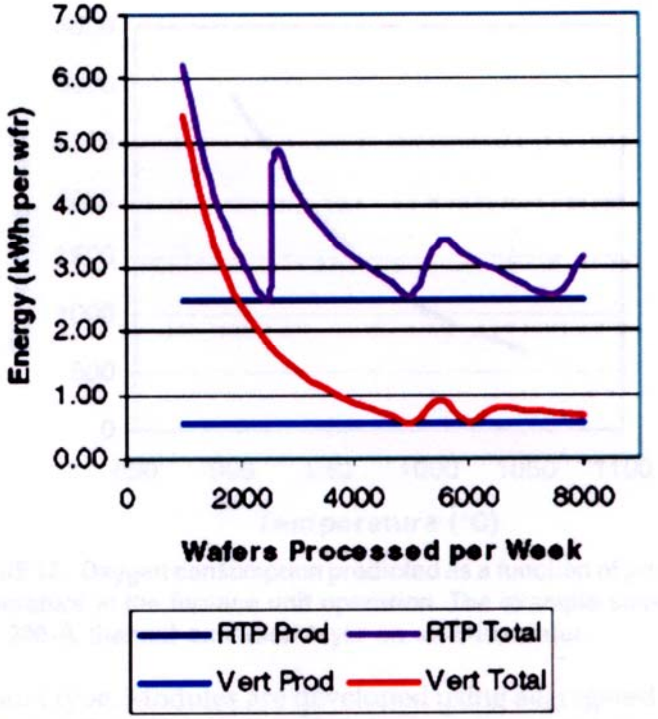

FIGURE 9. Energy consumption for growth of a 25-Å oxide layer as a function of equipment type (RTP vs vertical furnace), number of wafers processed per week, and total run time (production plus idle). The example shown is for 8-in. wafers.

Ref: Murphy et al
es&t 2003

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Power Requirements

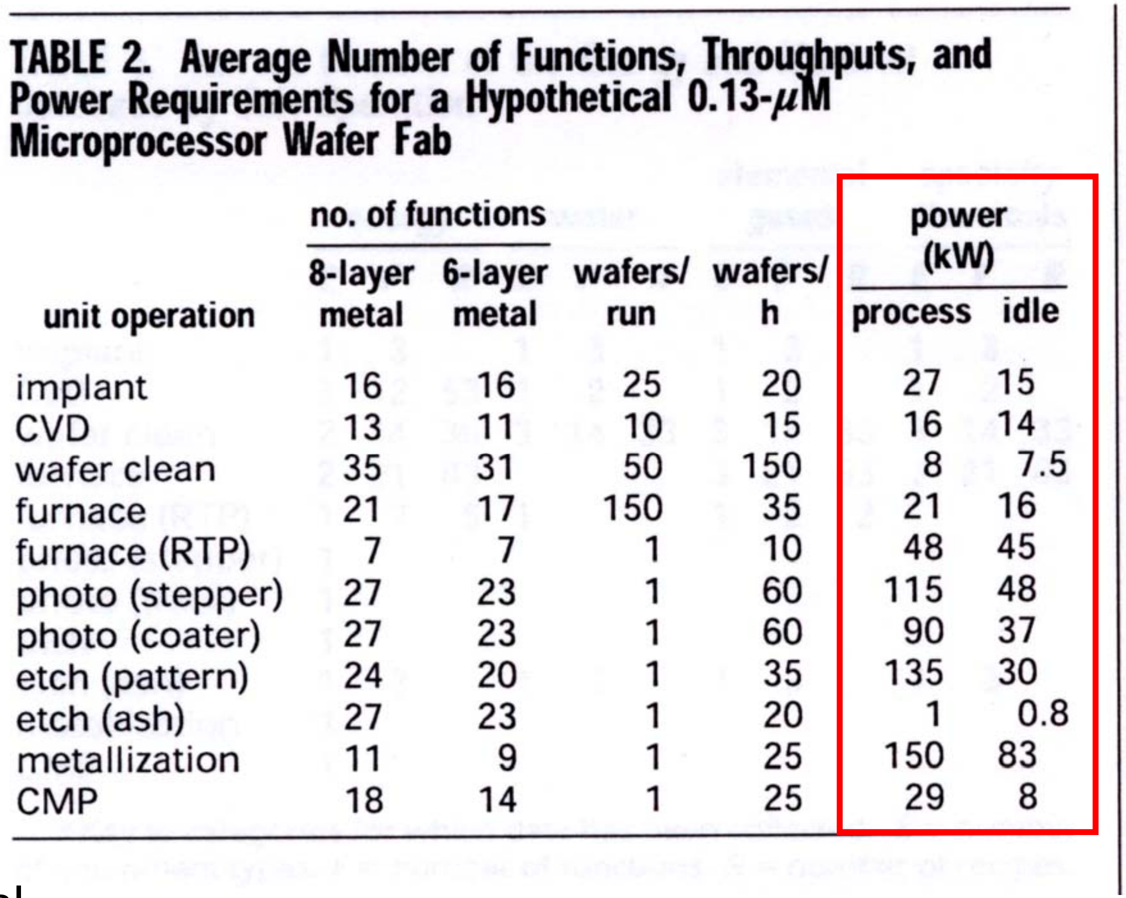

TABLE 2. Average Number of Functions, Throughputs, and Power Requirements for a Hypothetical 0.13-μM Microprocessor Wafer Fab

unit operation	no. of functions 8-layer metal	no. of functions 6-layer metal	wafers/ run	wafers/ h	power (kW) process	power (kW) 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

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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

$$5kW \leq P_o \leq 50kW$$

and

Material Process Rates

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

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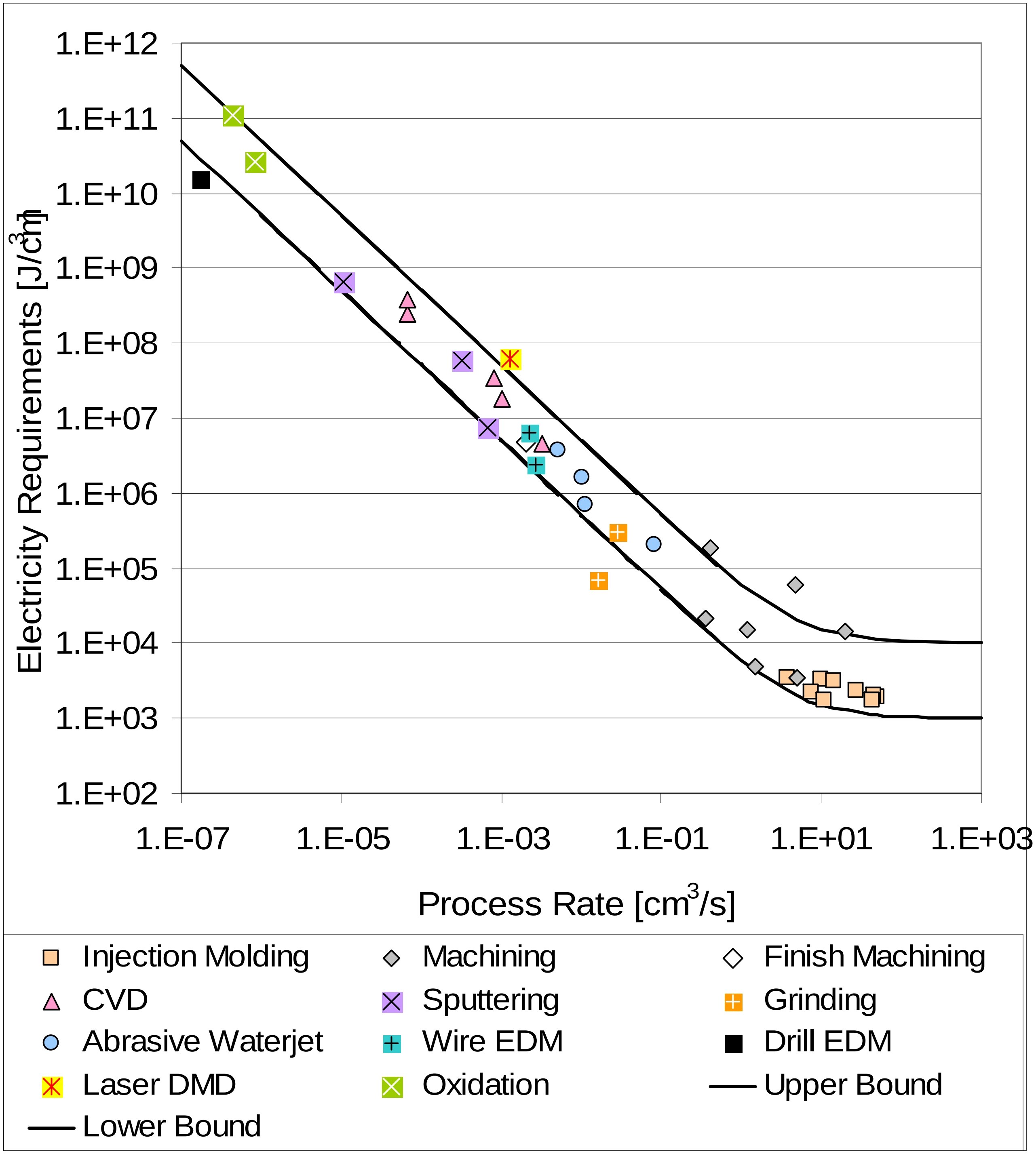
Specific Energy Requirements J/cm^3 for Various Mfg Processes



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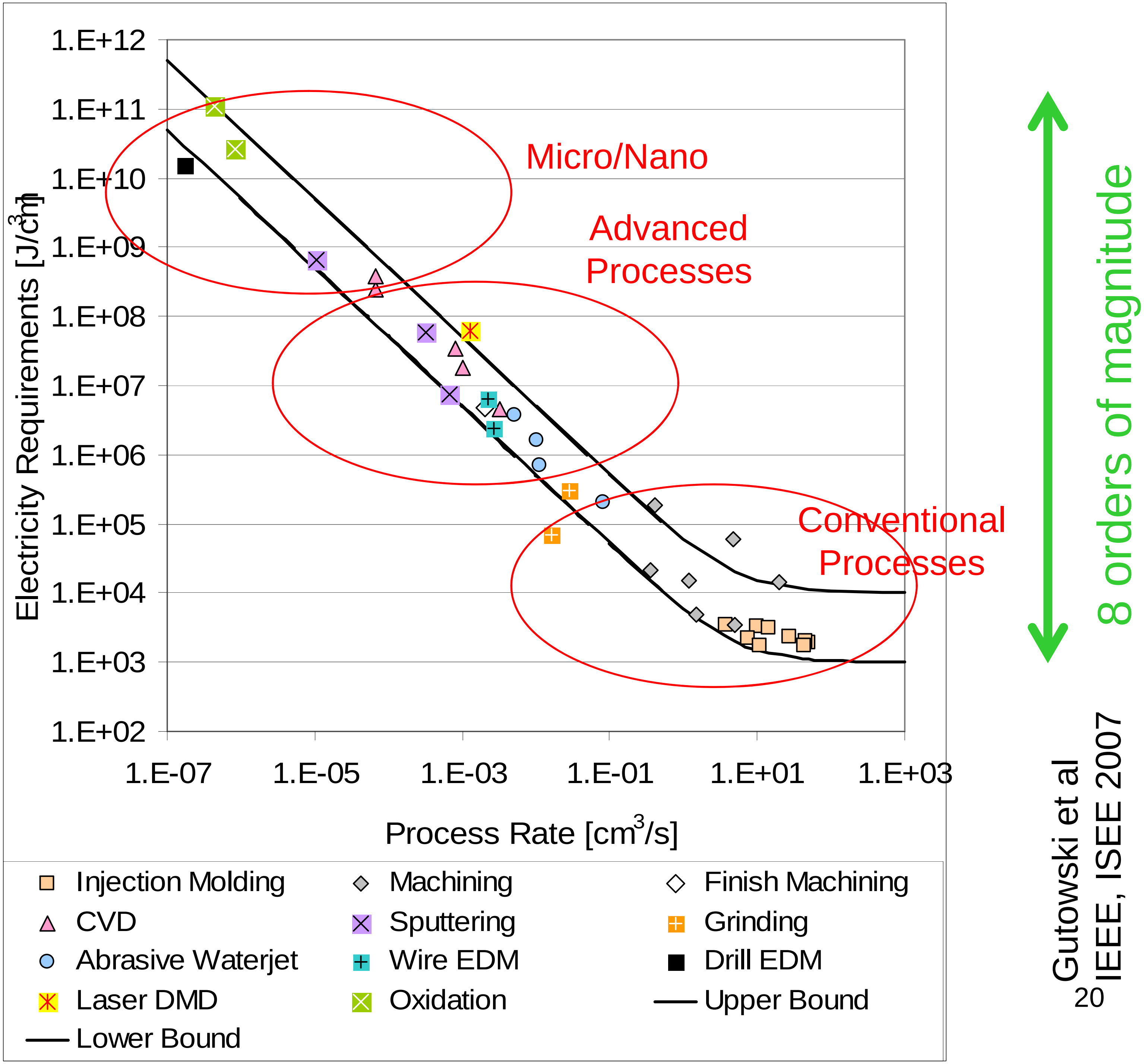
Specific Energy Requirements J/cm^3 for Various Mfg Processes



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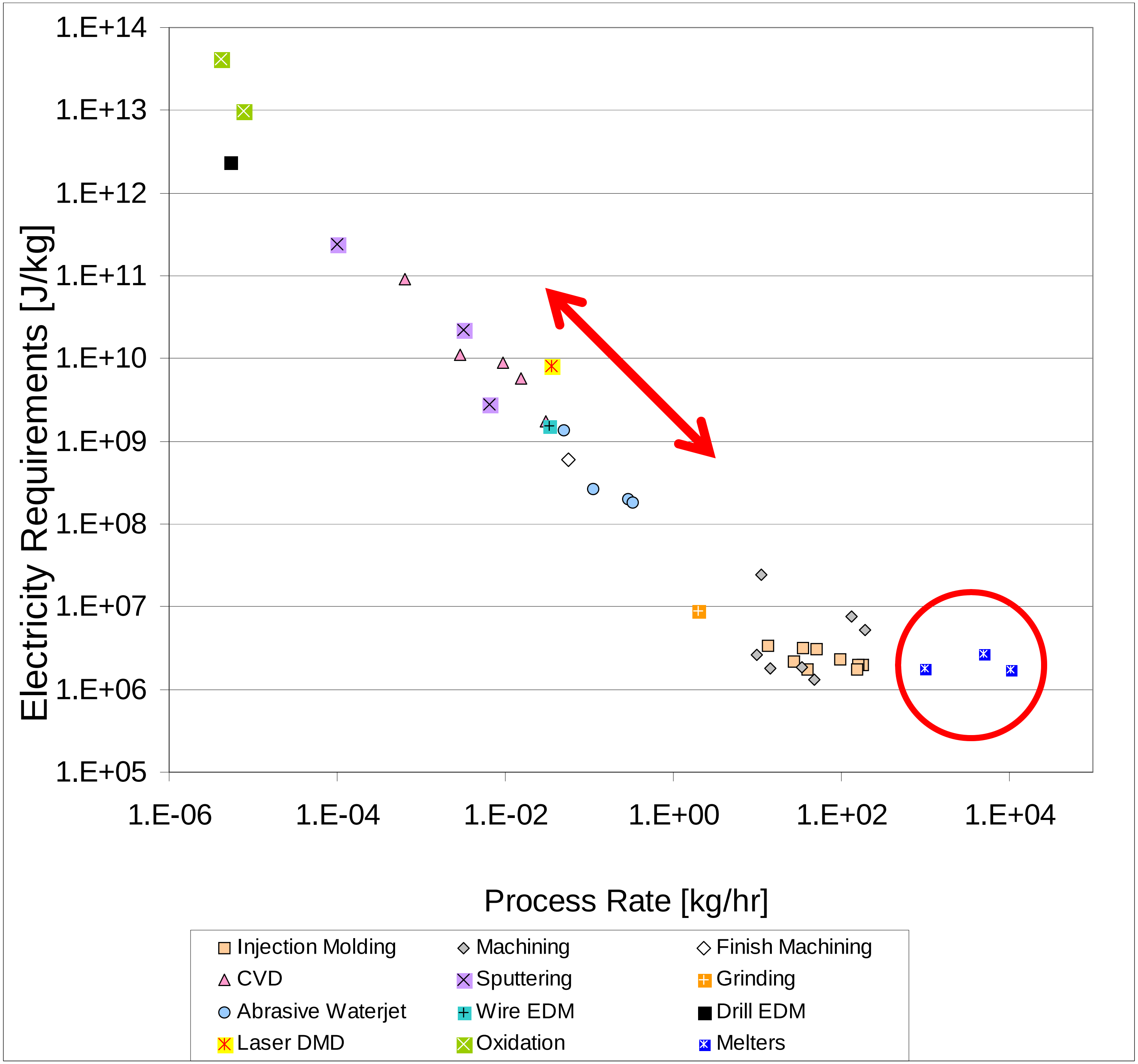

Gutowski et al
IEEE, ISEE 2007

Keep in Mind

- This is intensity not total used
- This is at the device
    - – loses at energy conversion not included
    - – investment into materials not included
    - – infrastructure not included
- Suggestive of efficiency

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Why are these energy intensities so high?

- stable and declining energy prices
- demand for small devices
- vapor phase processes with slow deposition rates
- efficiency used to enhance performance
- never the less, the trajectory of individual processes is toward faster rates and lower energy intensities

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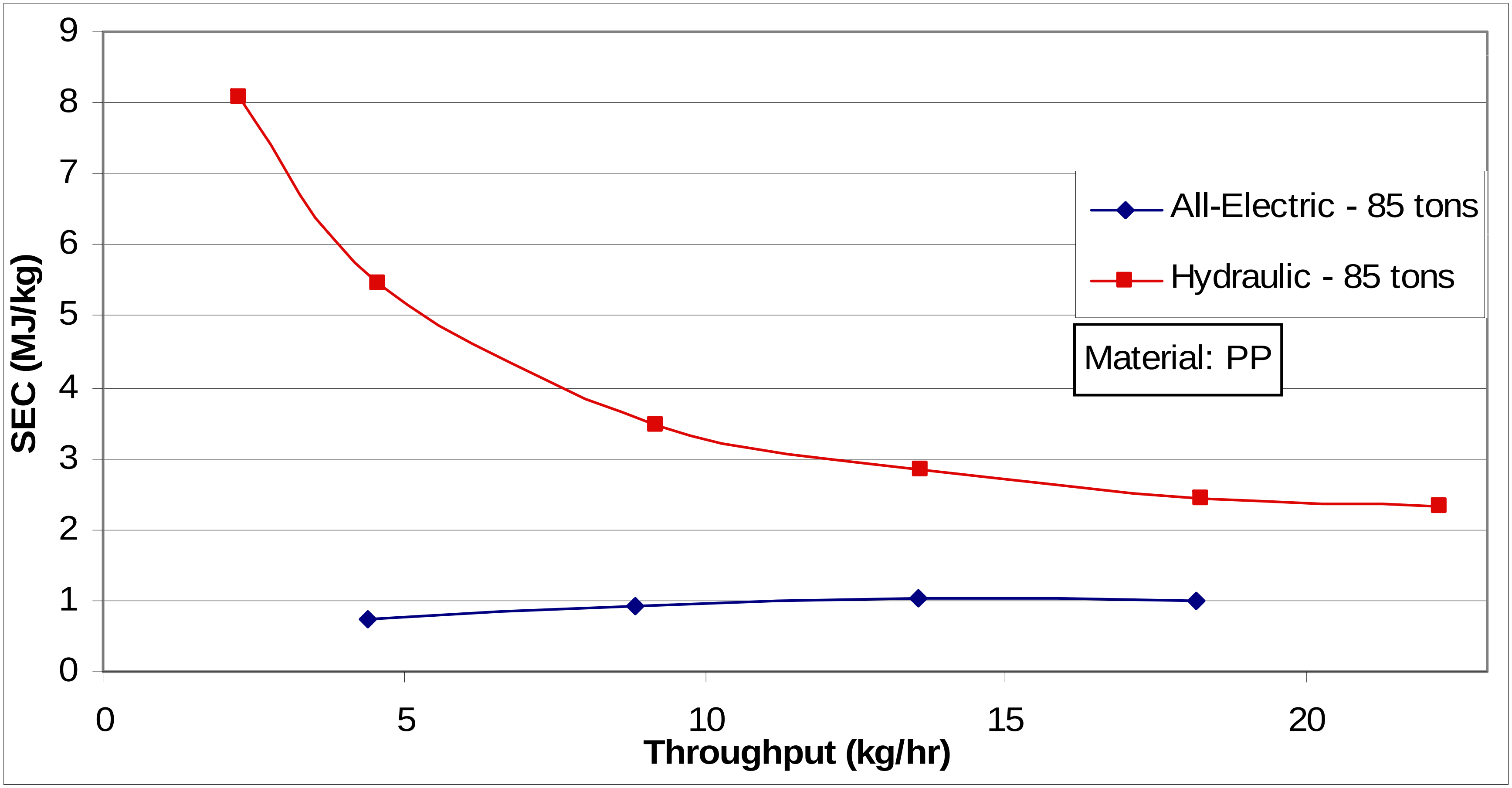
All Electric Vs Hydraulic Injection Molding Machines



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Source: [Thiriez 2006]

Exergy Analysis including Chemical Composition

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

- $B = B^{ph} + B^{ch}$
- $B^{ph}(T=T_o, P=P_o) = 0$
  - – this is the "restricted dead state*"
- when $B = B^{ph} = 0$, and
- $B^{ch}(\mu^* = \mu_o) = 0$
  - – this is the "dead state"

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Work Rate for Mfg Process

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

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

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

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

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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].

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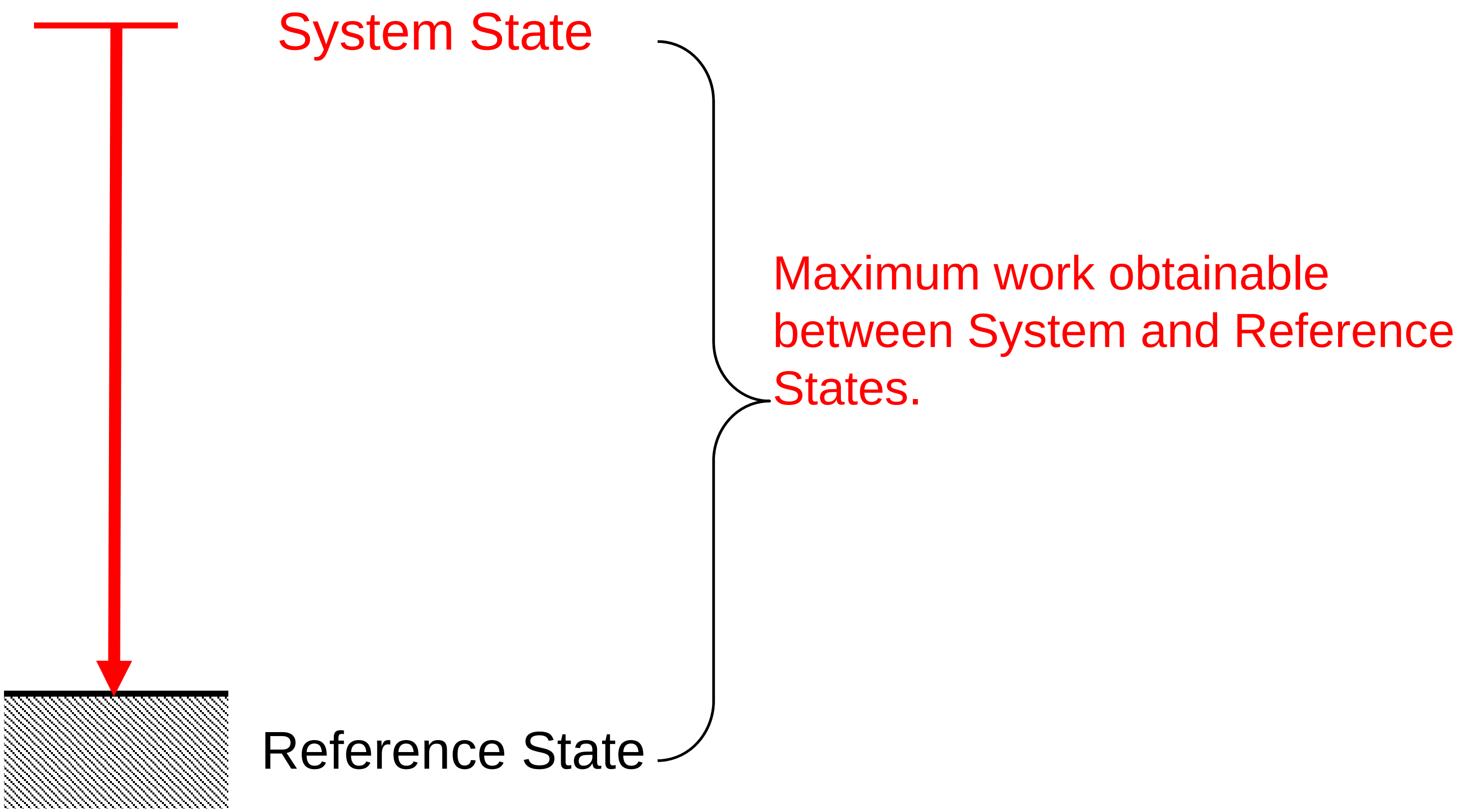
Exergy



System State

Maximum work obtainable between System and Reference States.

Reference State

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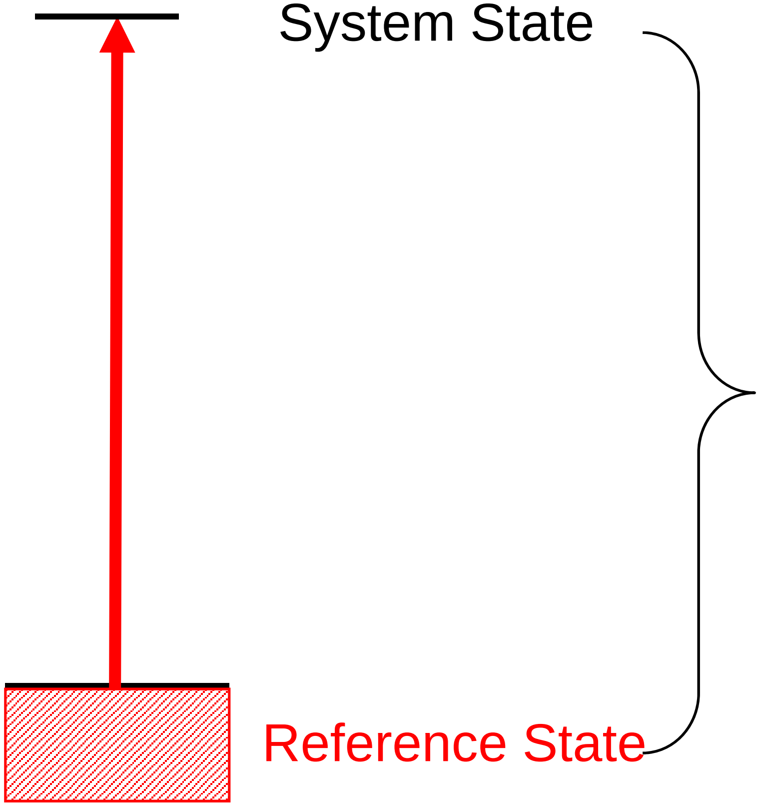
Exergy



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

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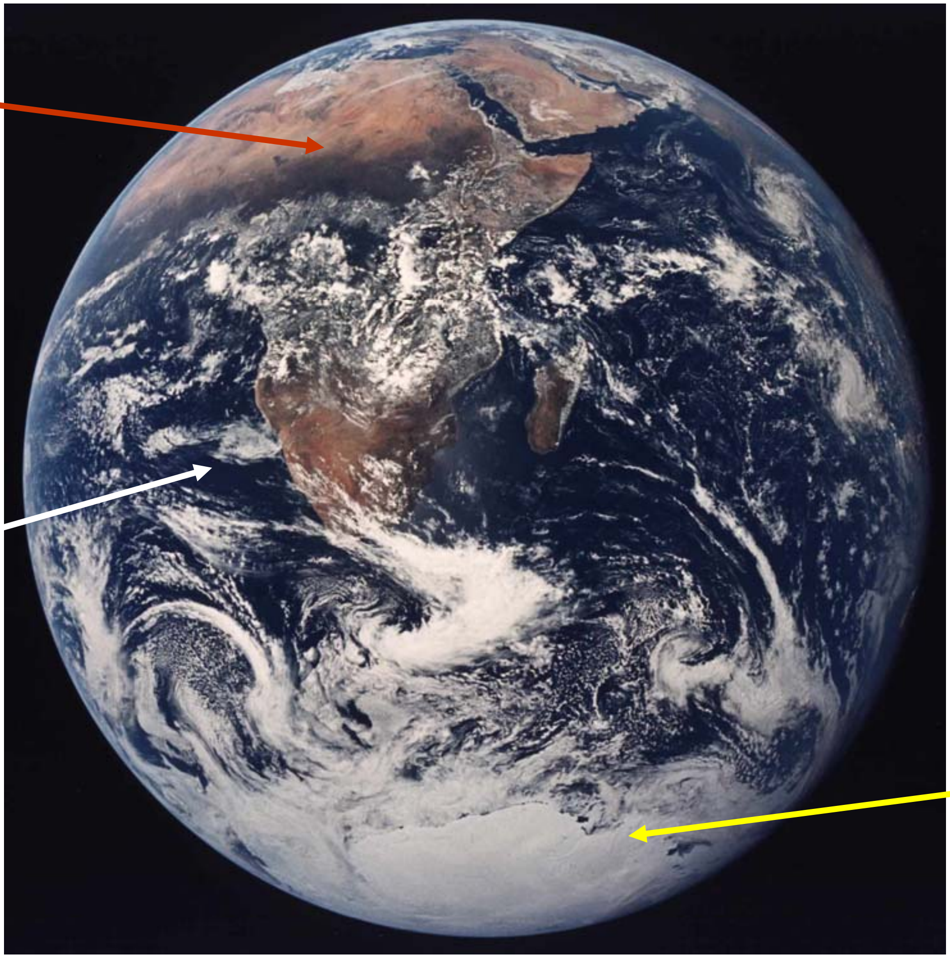
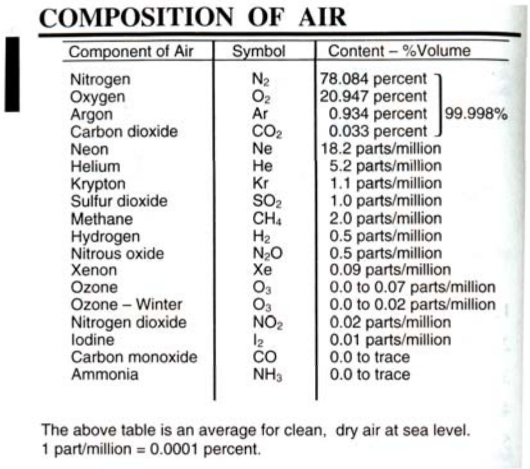
Chemical Properties referenced to the "environment"

Crust

Oceans



Atmosphere



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.

T_o = 298.2 K,

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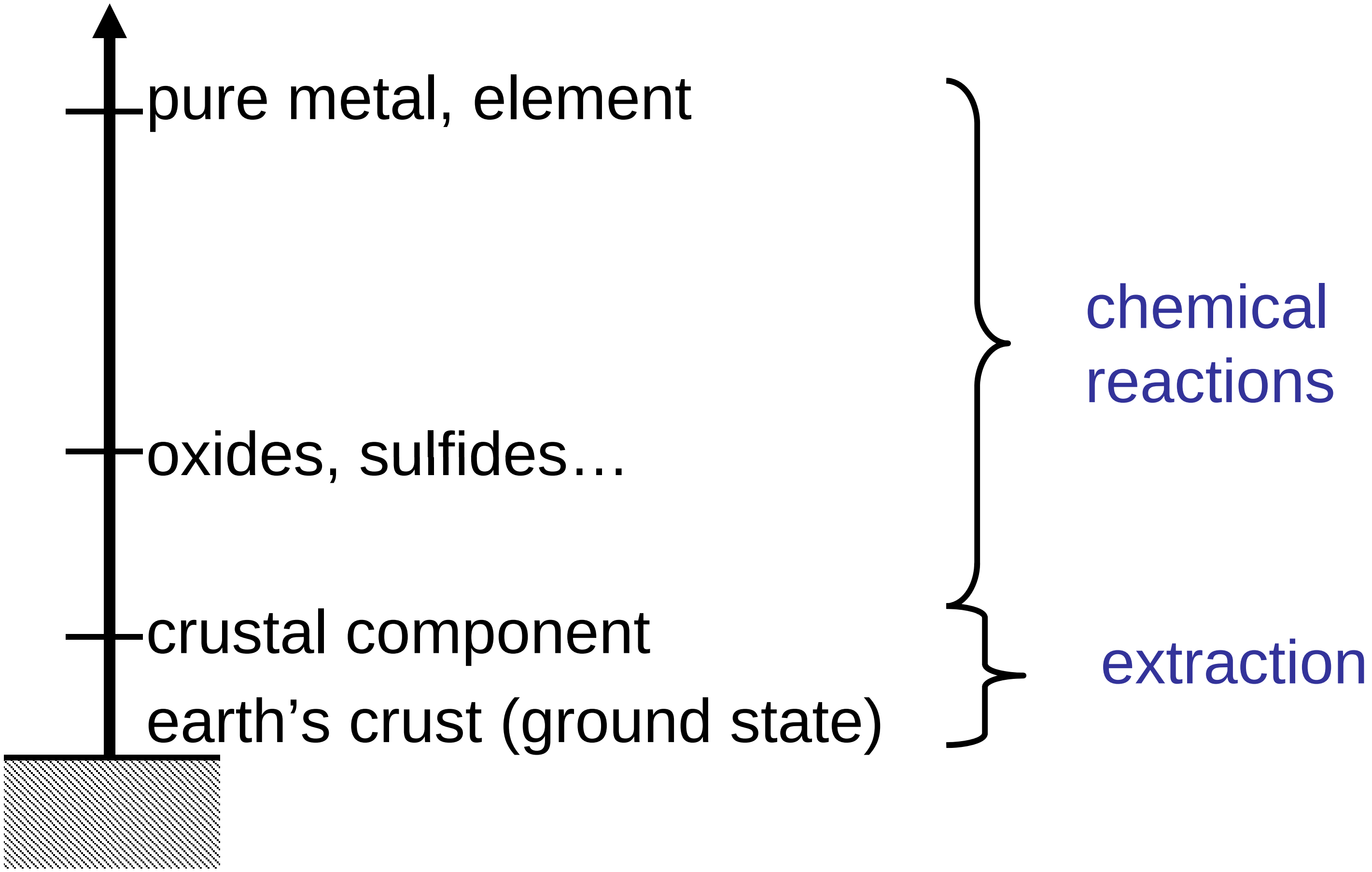
P_o = 101.3 kPA

Exergy Reference System



pure metal, element

oxides, sulfides…

crustal component

earth’s crust (ground state)

chemical reactions

extraction

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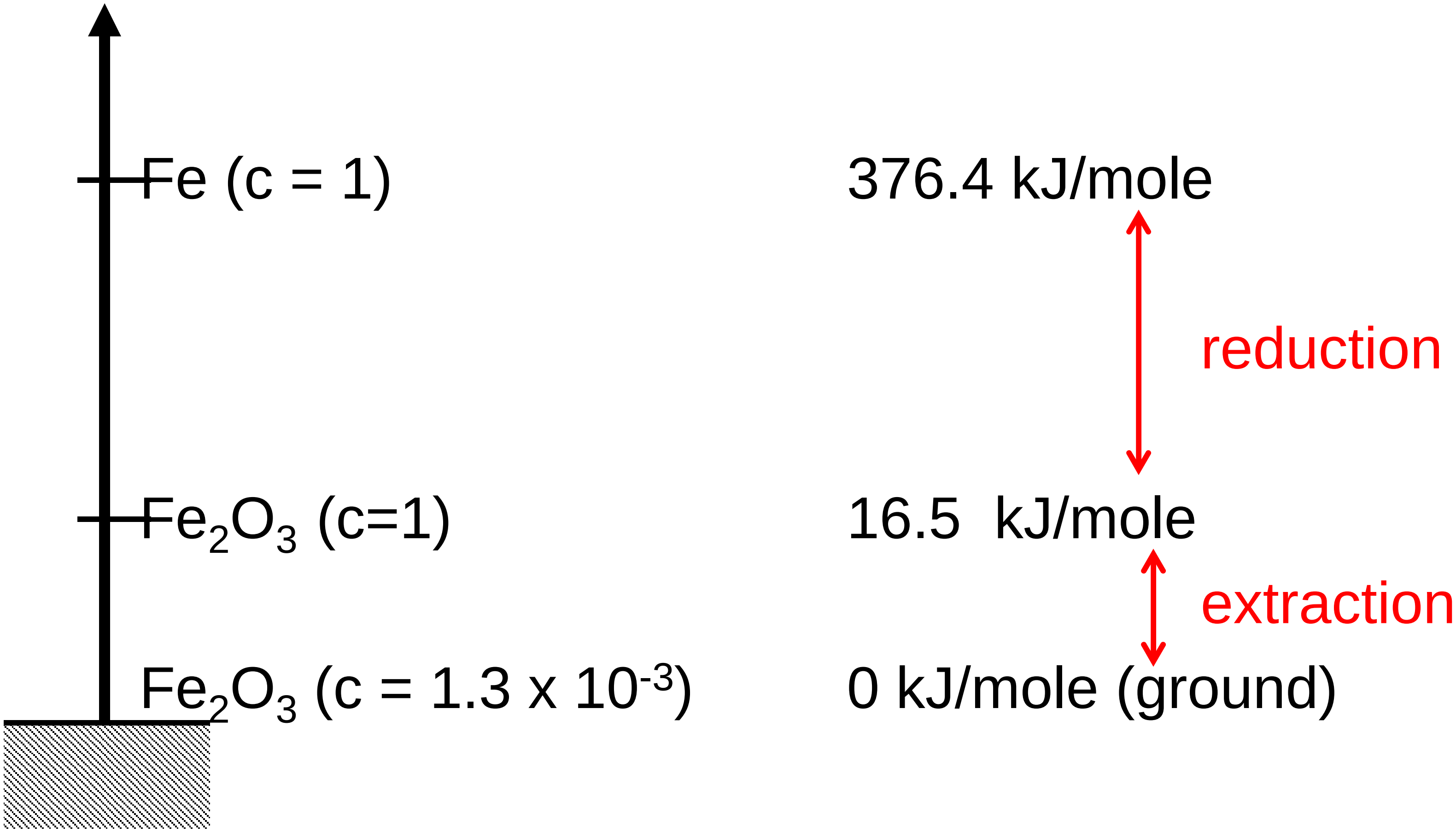
Example; making pure iron from the crust



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)

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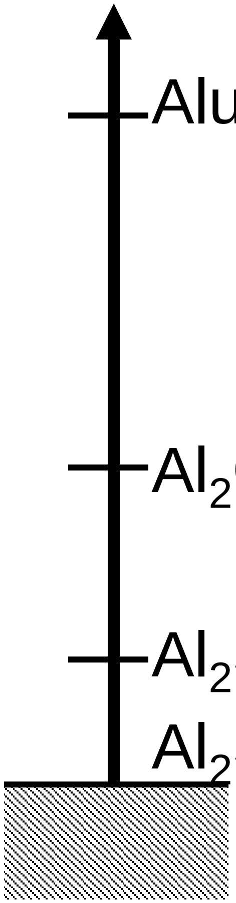
Exergy Reference System



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)

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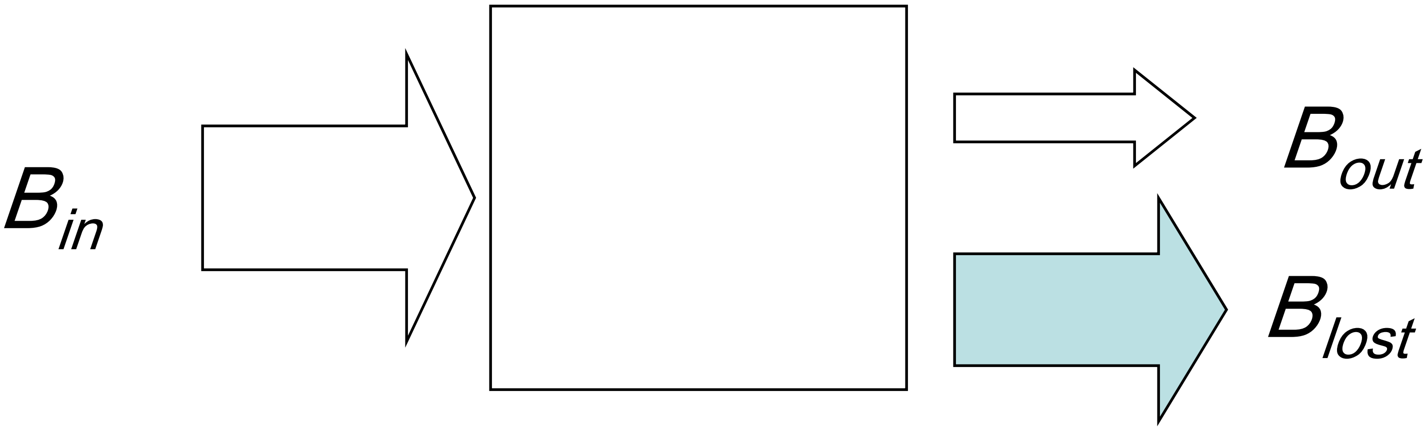
Exergy Accounting



$$B_{in} - B_{out} = B_{lost}$$

Chemical Reactions

stoichiometric mass balance

$$v_a R_a + v_b R_b + \ldots. \rightarrow v_j \Pi_j + v_k \Pi_k + \ldots$$

exergy "balance"

$$v_a b_{R_a} + v_b b_{R_b} + \ldots. - v_j b_{\Pi_j} - v_k b_{\Pi_k} = B_{lost}$$

where exergy b is given in kJ/mole

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Efficiency Measures: Degree of Perfection

$$\eta_p = \frac{B_{useful\ output}}{B_{in}}$$

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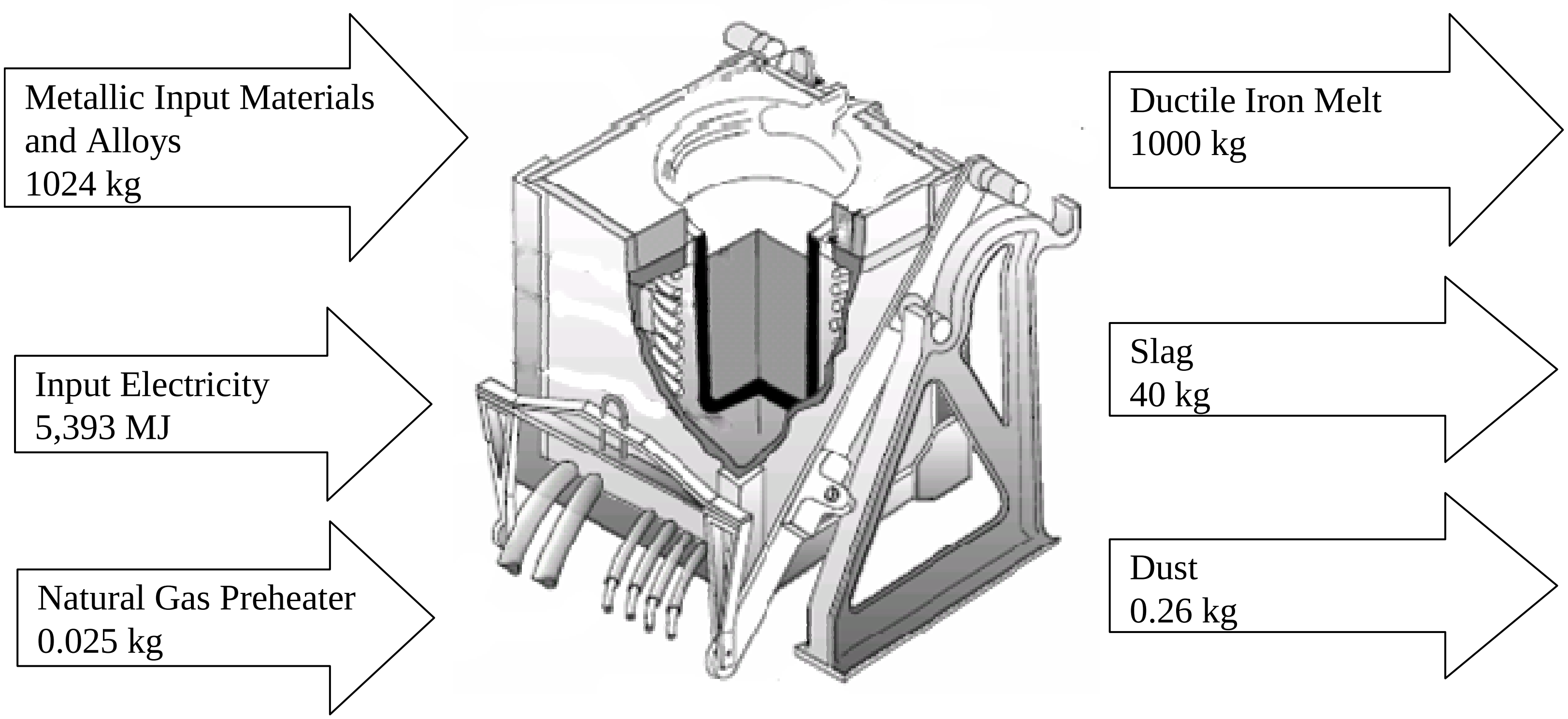
Batch Induction Melter Inputs and Outputs

Ductile Iron – Batch Electric Induction Exergy Analysis



Metallic Input Materials and Alloys
1024 kg

Input Electricity
5,393 MJ

Natural Gas Preheater
0.025 kg

Ductile Iron Melt
1000 kg

Slag
40 kg

Dust
0.26 kg

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

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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%**				

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*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*	2,455,000

*not including utility losses

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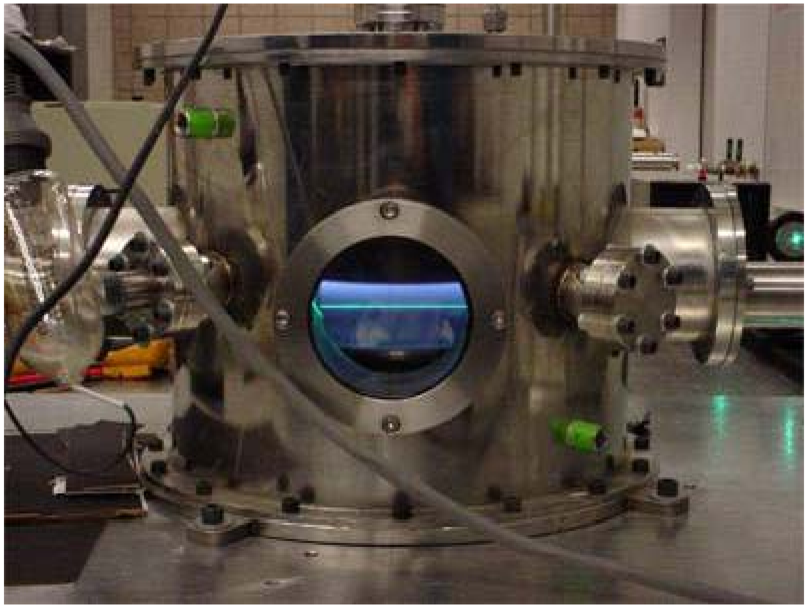
Plasma Enhanced Chemical Vapor Deposition (CVD)



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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	

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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

Degree of Perfection

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

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

*not including utility losses

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Data from Sarah Boyd et. al. (2006)

Reasons for a Low Efficiencies

- Inefficient use of materials
- Use of high exergy materials (ultra-pure)
- Use of high exergy Aux. mat'ls (CH_4)
- Low yields
- Low processing rates

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Manufacturing's Role in a Low Carbon Future

- Many small pieces
- Contribution to solutions
- Materials management
- Strong rate effect…
- Process redesign issues

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Most of these results can be found

- on our website:

  http://web.mit.edu/ebm/www/index.html

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