Energy & Exergy Efficiency of Manufacturing Processes

Tim Gutowski

Department of Mechanical Engineering

Massachusetts Institute of Technology

Outline

- Thermodynamic Framework
- Work and Exergy
- Mfg Process Use of Electricity
- Exergy Analysis
- Efficiency

Figure from Gyftopoulos & Berreta

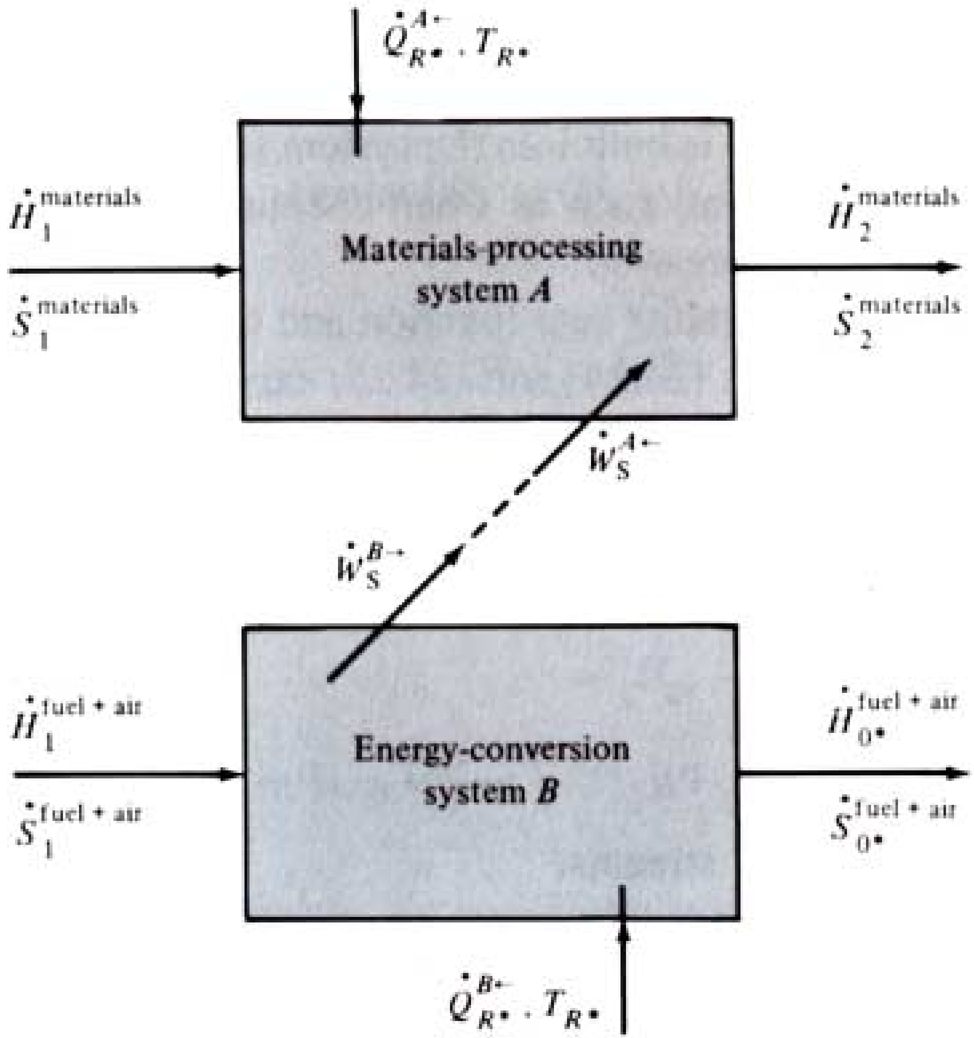
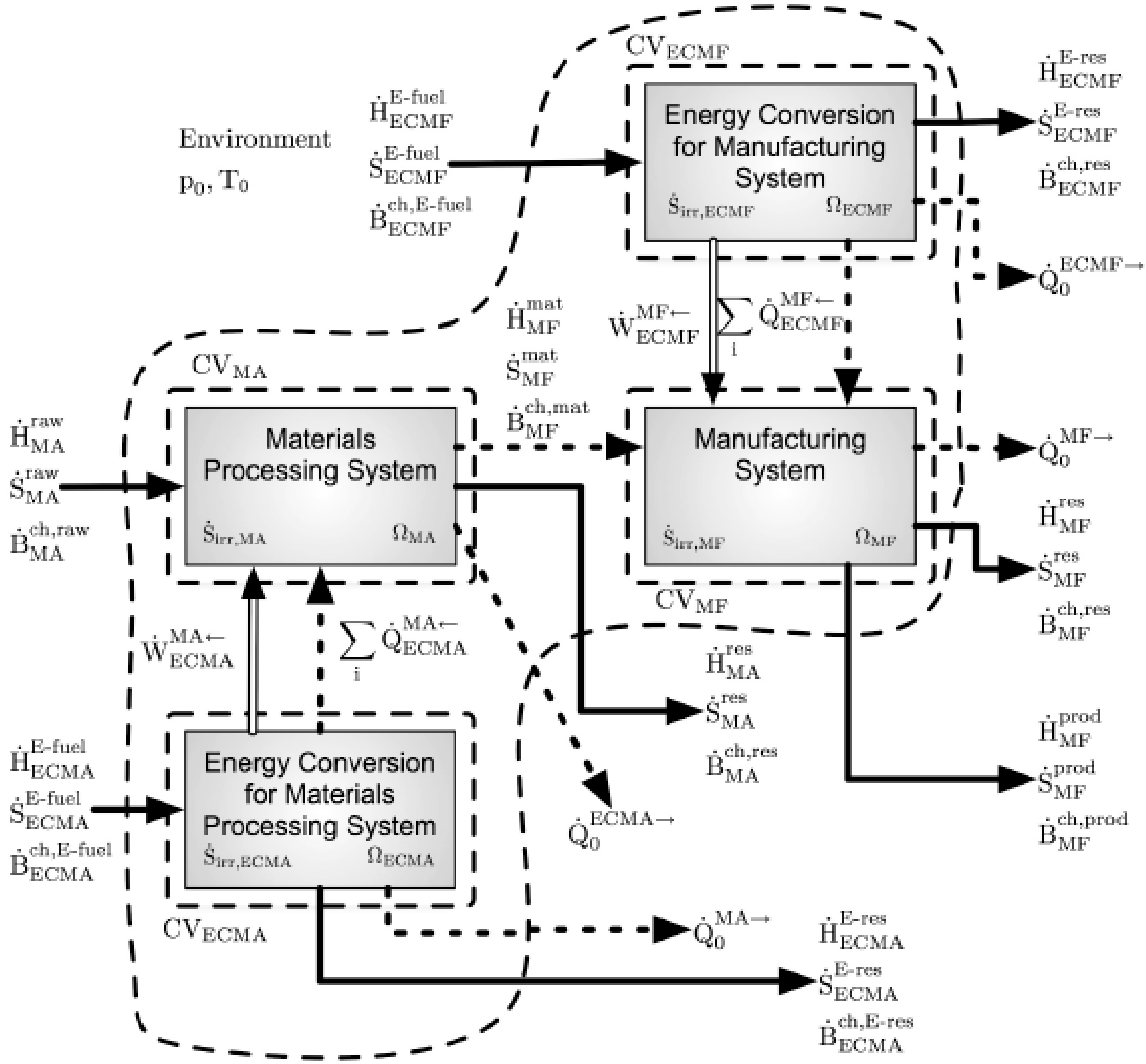


Figure 24.2 The burning of a fuel-air mixture in the energy-conversion system provides the work needed to process the bulk-flow stream through the materials-processing system.



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

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

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

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

Branham et al IEEE ISEE 2008

Exergy and Work

$$B = (H - T_o S)_{P,T} - (H - T_o S)_{P_o,T_o}$$

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

Branham et al IEEE ISEE 2008

An Important Simplification

Consider the simplification where $\dot{Q}_{in} = 0$, and we focus on the material processed, therefore material in = material out = material processed, all at rate, $\dot{N}$.

$$\dot{W}_{ECMF}^{MF\leftarrow} = \Delta\dot{B} + T_0\dot{S}_{irr,MF} = \dot{N}\Delta b + T_0\dot{S}_{irr,MF}$$

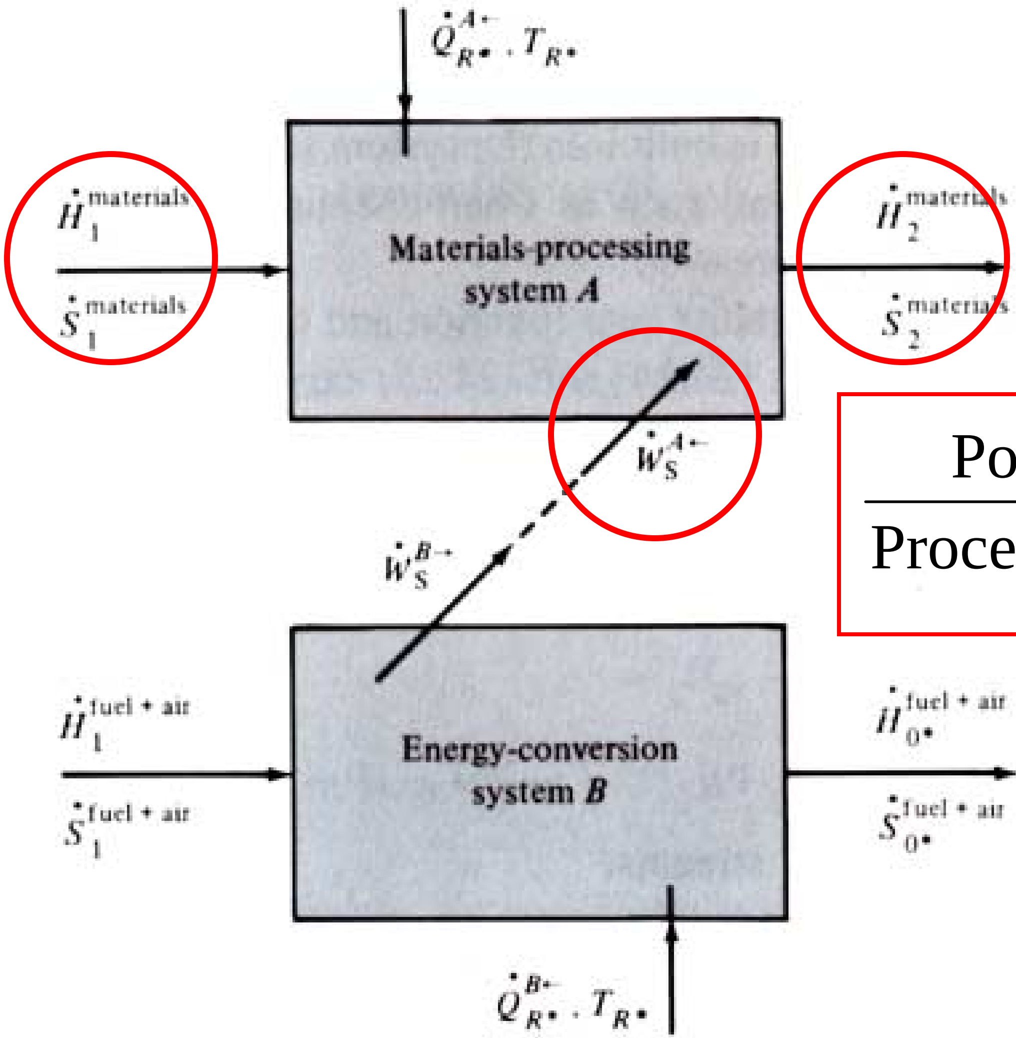
$$w = \frac{\dot{W}_{ECMF}^{MF\leftarrow}}{\dot{N}} = \Delta b + \frac{T_0\dot{S}_{irr,MF}}{\dot{N}}$$

$$\dot{B}_i = \dot{N}[(h_i - T_o s_i) - (h_{i,o} - T_o s_{i,o})] = \dot{N}b$$

Mfg Process Use of Electricity

1. Machining (rough and finish)
2. Grinding
3. Abrasive Waterjet
4. EDM (wire and drill)
5. Injection Molding
6. CVD
7. Sputtering
8. Thermal Oxidation
9. Laser DMD

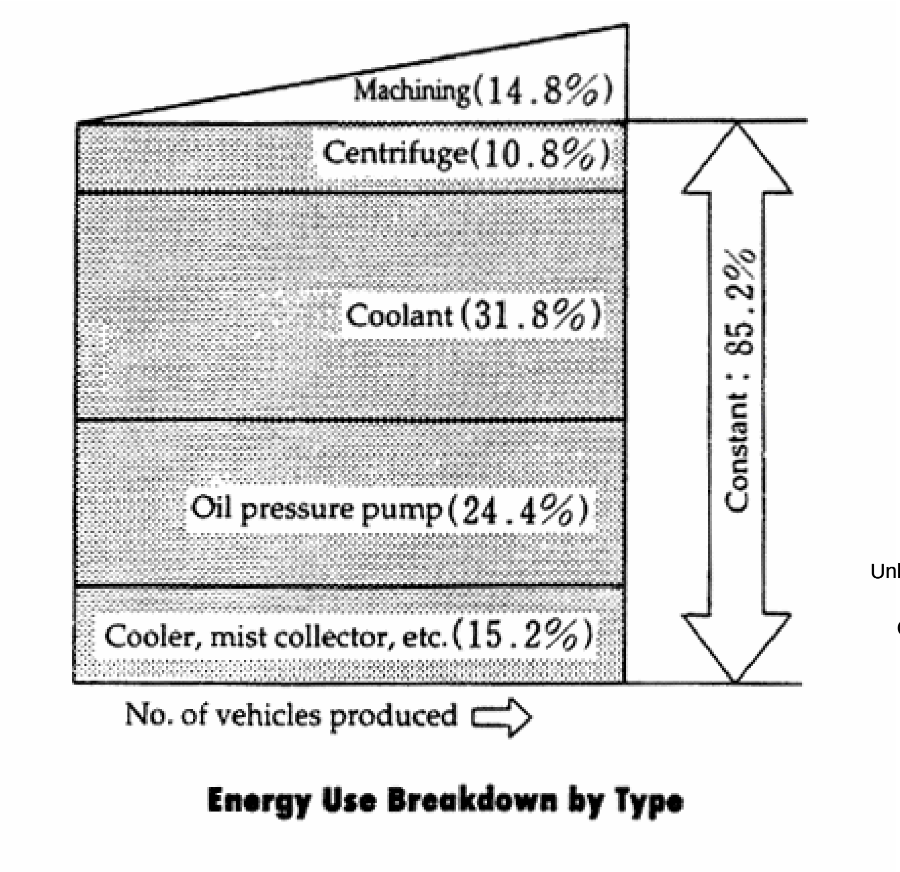
Figure from Gyftopoulos & Berreta



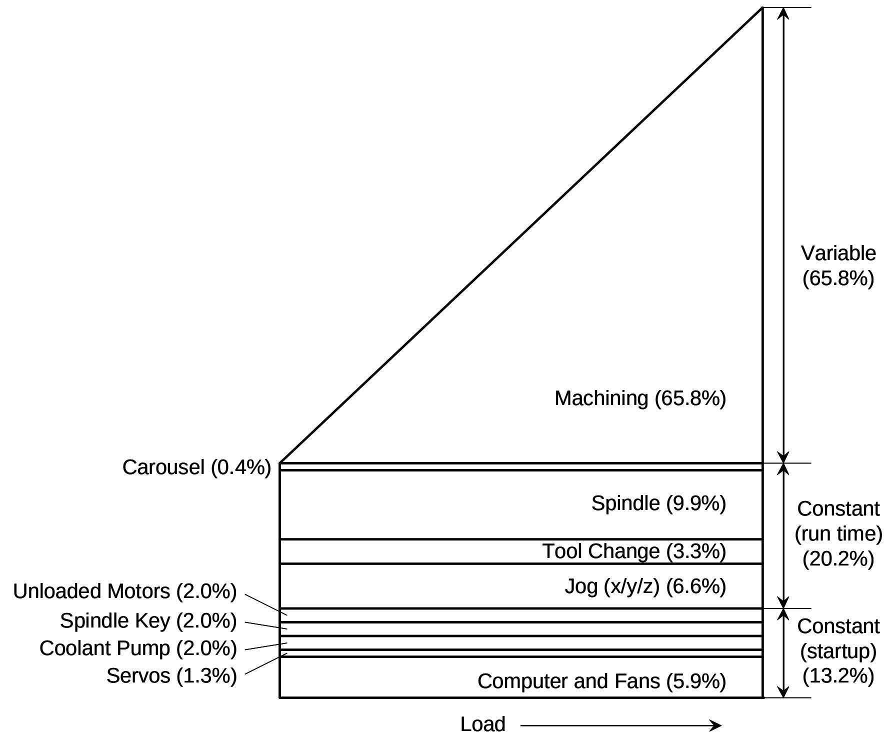
$$\frac{\text{Power}}{\text{Process Rate}} = \text{Energy Intensity}$$

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.

Energy Requirements at the Machine Tool



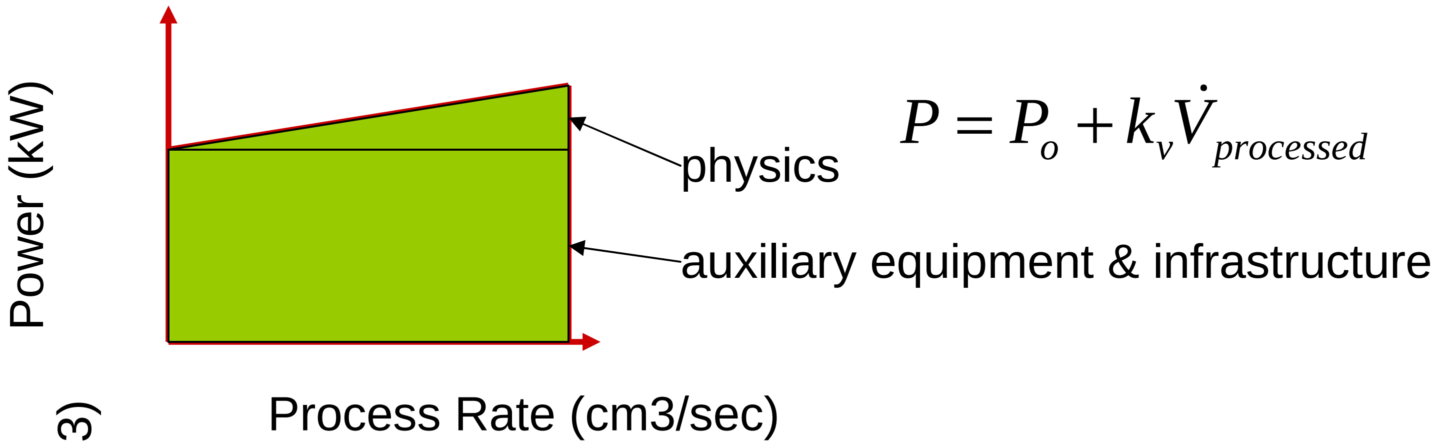
Production Machining Center



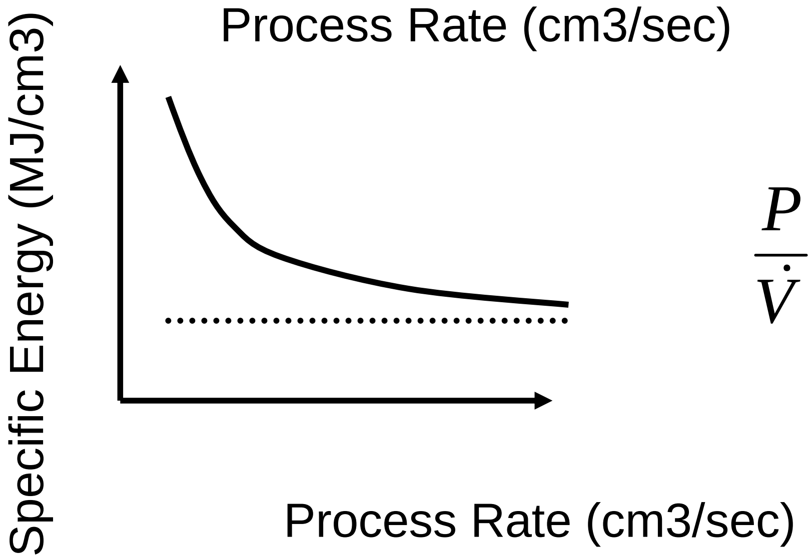
Automated Milling Machine

From Toyota 1999, and Kordonowy 2002.

Electric Energy Intensity for Manufacturing Processes

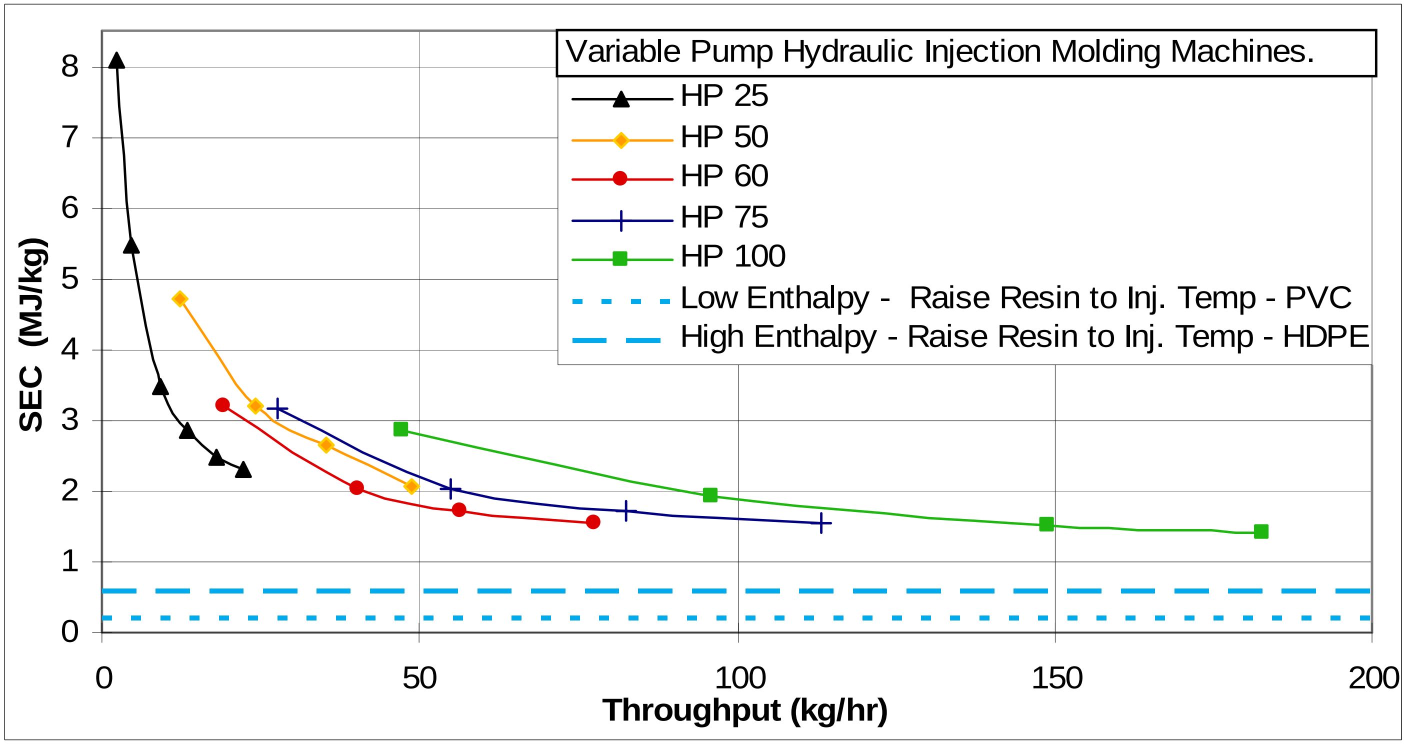


$$P = P_o + k_v \dot{V}_{processed}$$



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

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

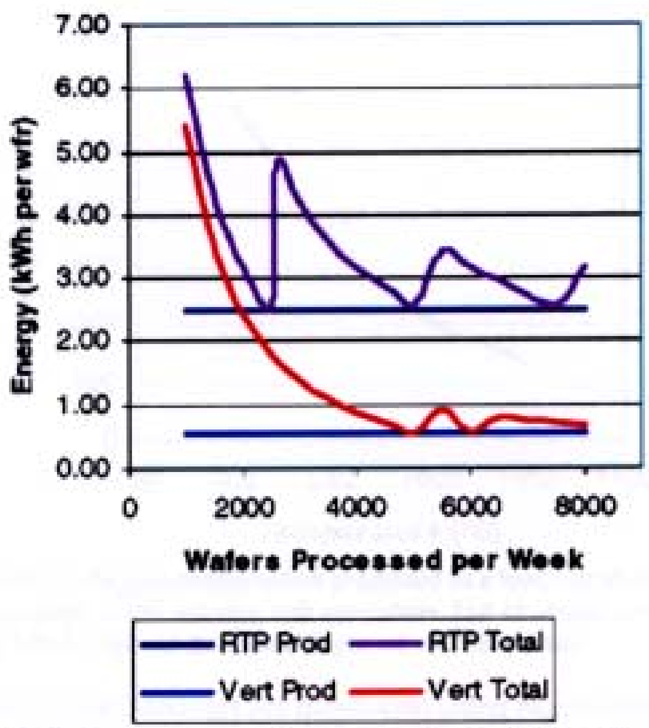


FIGURE 9. Energy consumption for growth of a 25-Å oxide layer as a function of equipment type (RTP vs vertical furnace), number of wafers processed per week, and total run time (production plus idle). The example shown is for 8-in. wafers.

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	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

Process Name	Power Required (kW)	Process Rate (cm^3/s)		Electricity Required (J/cm^3)	References
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

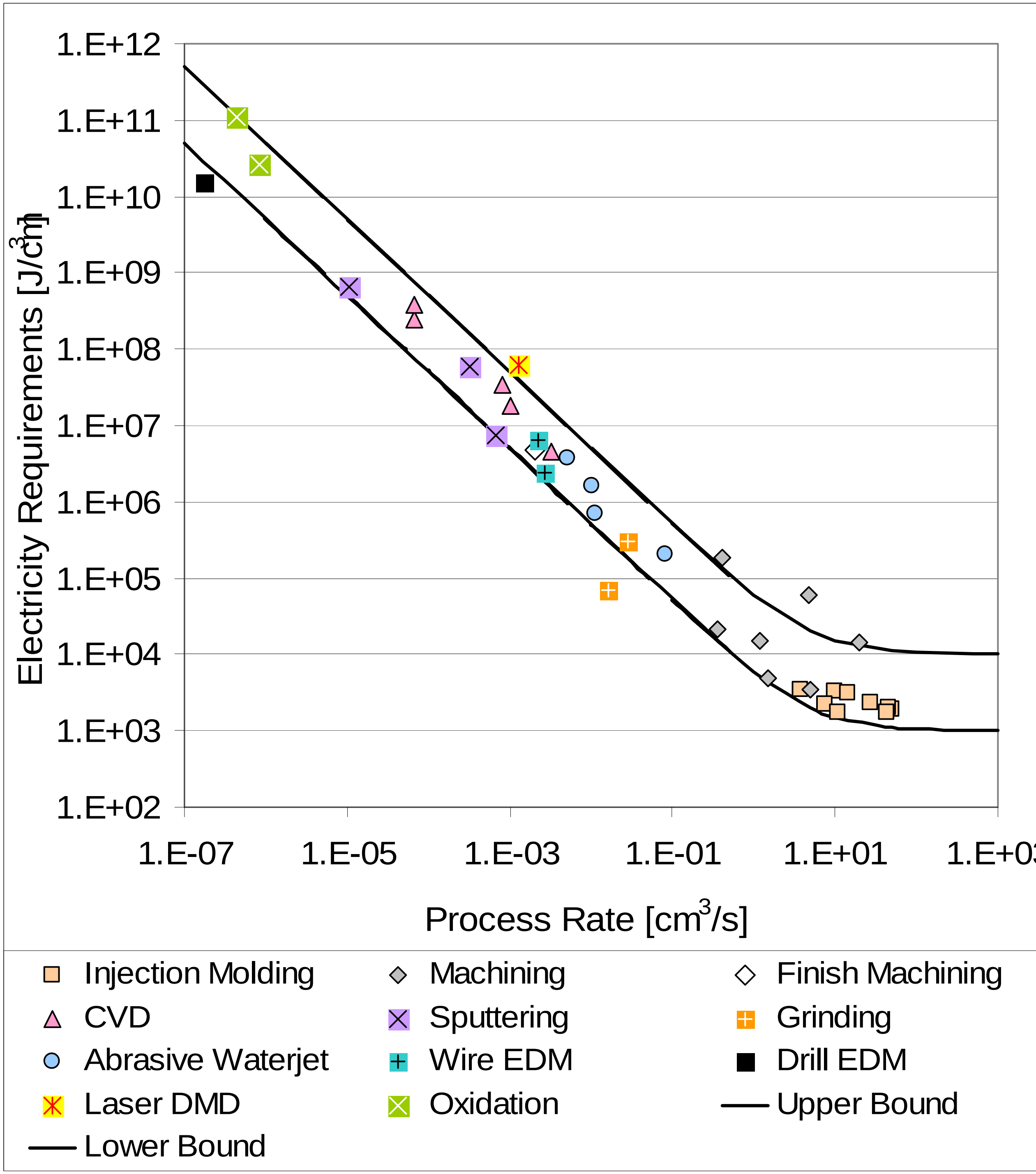
$$5kW \leq P_o \leq 50kW$$

and

Material Process Rates

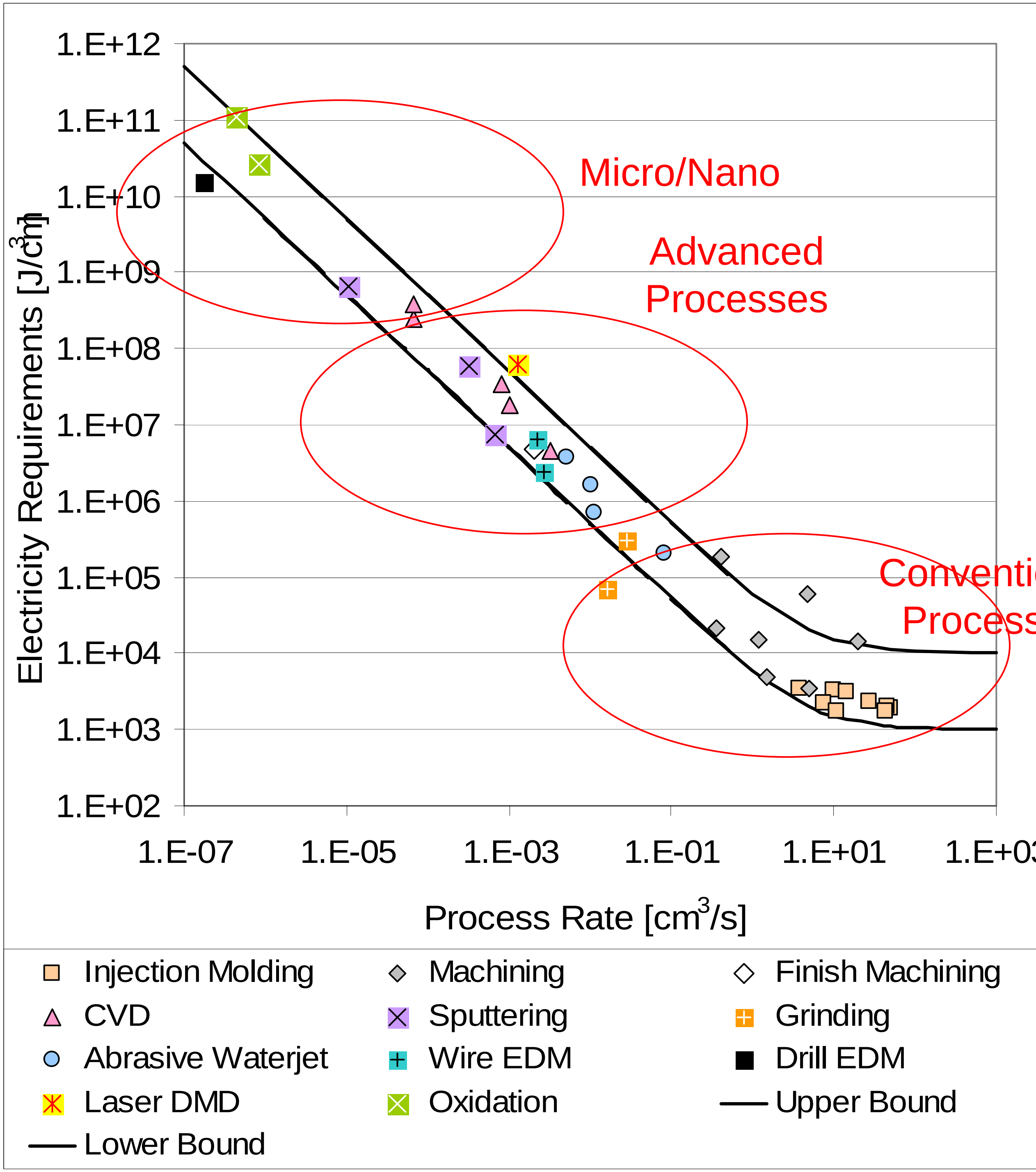
$$10^{-7}\ \text{cm}^3/\text{sec} \leq \dot{V} \leq 1\,\text{cm}^3/\text{sec}$$

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



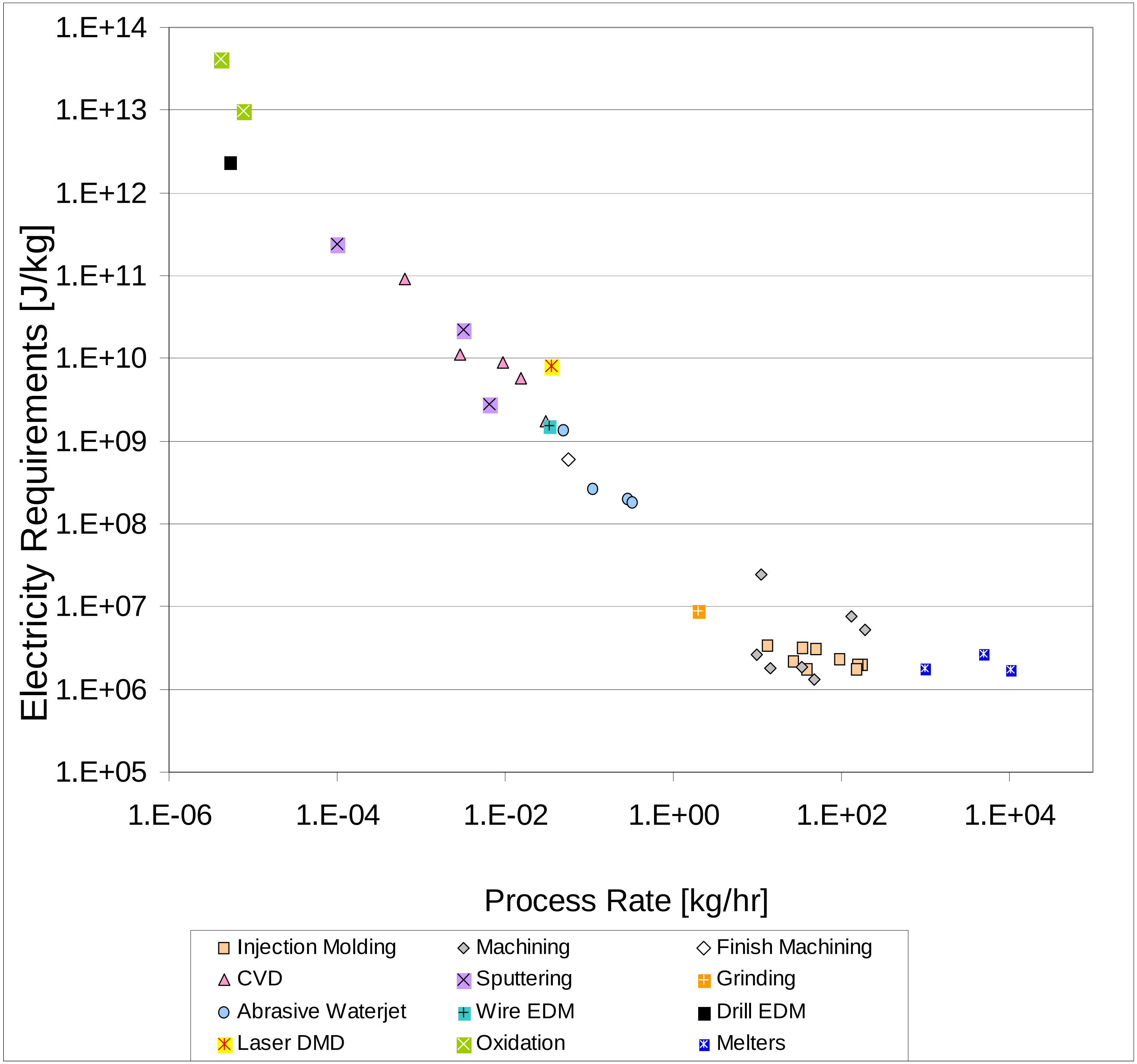
Gutowski et al
IEEE, ISEE 2007

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



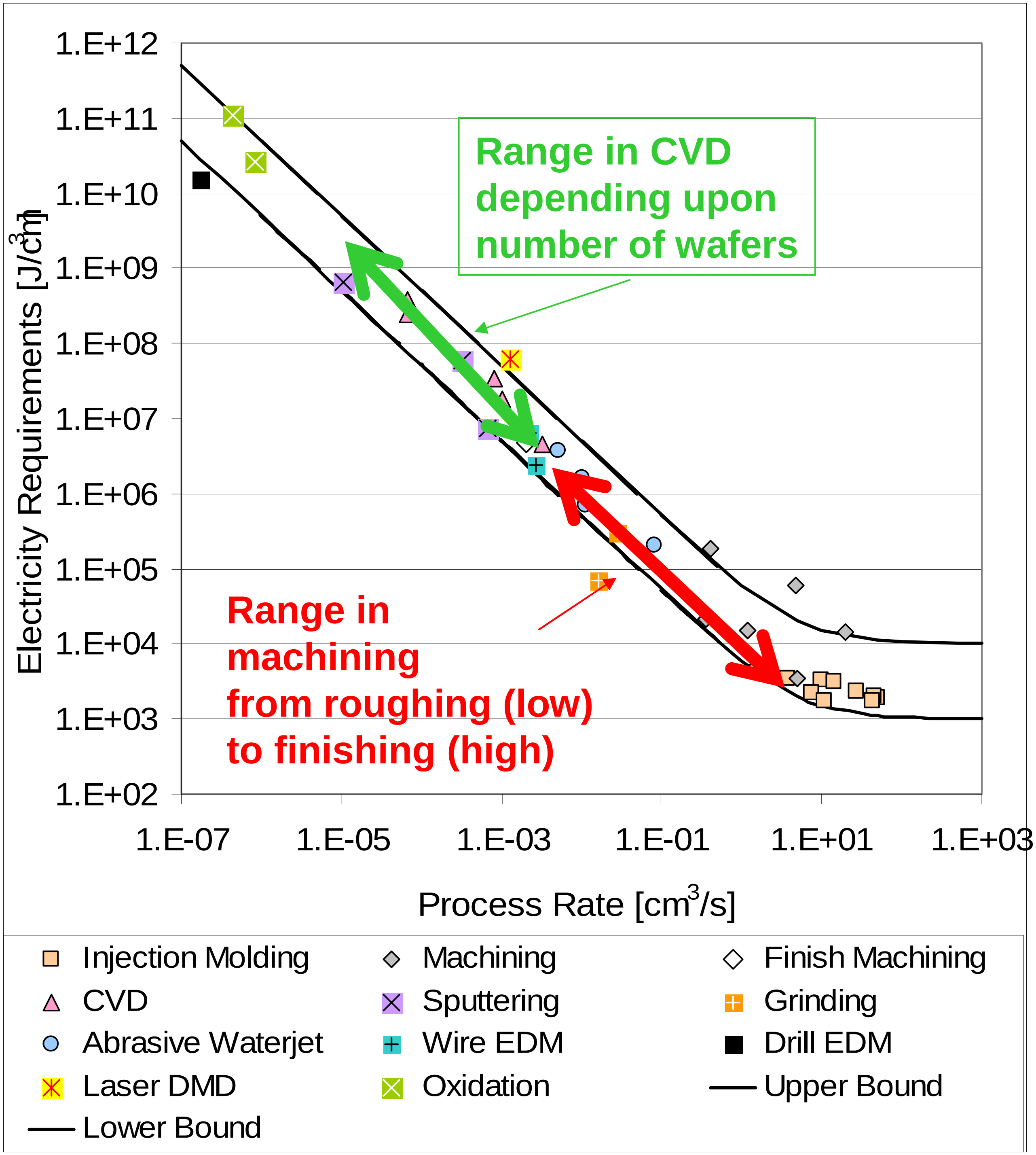
8 orders of magnitude

Gutowski et al
IEEE, ISEE 2007

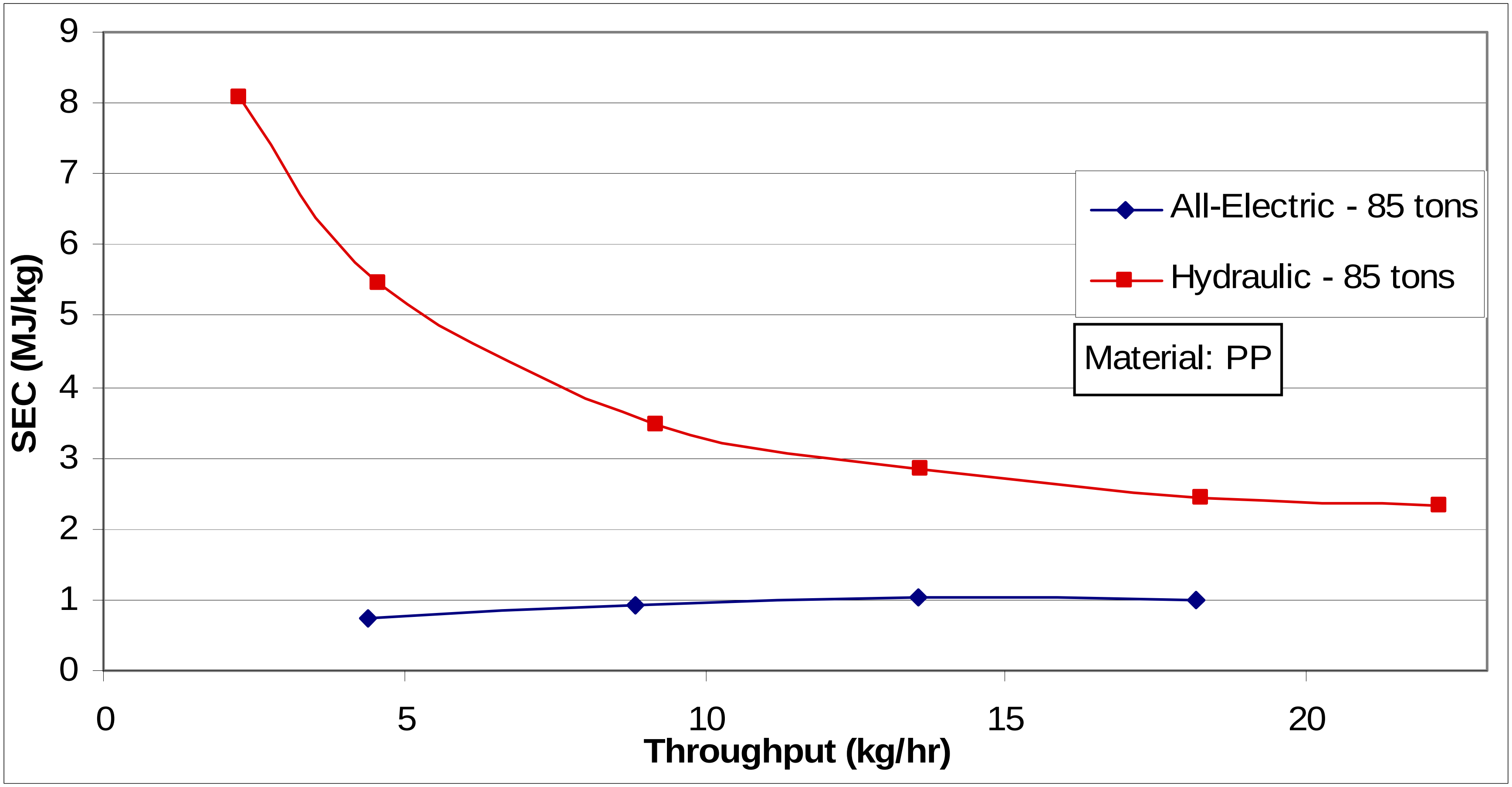


Gutowski et al
IEEE, ISEE 2007

Individual Processes can vary by 2 or 3 orders of magnitude depending upon operational parameters



All Electric Vs Hydraulic Injection Molding Machines



Source: [Thiriez 2006]

Electricity Use in Mfg Processes

- Intensity Vs total used
- suggestive of efficiency
- this is at the device
  - loses at energy conversion not included
  - investment into materials not included
  - infrastructure not included
- leveraging of low energy prices apparent
- strong rate effect

Exergy Analysis including Chemical Composition

$$B = (H - T_o S)_{P,T,\mu} - (H - T_o S)_{P_o,T_o,\mu_o}$$

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

Work Rate for Mfg Process

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

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

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

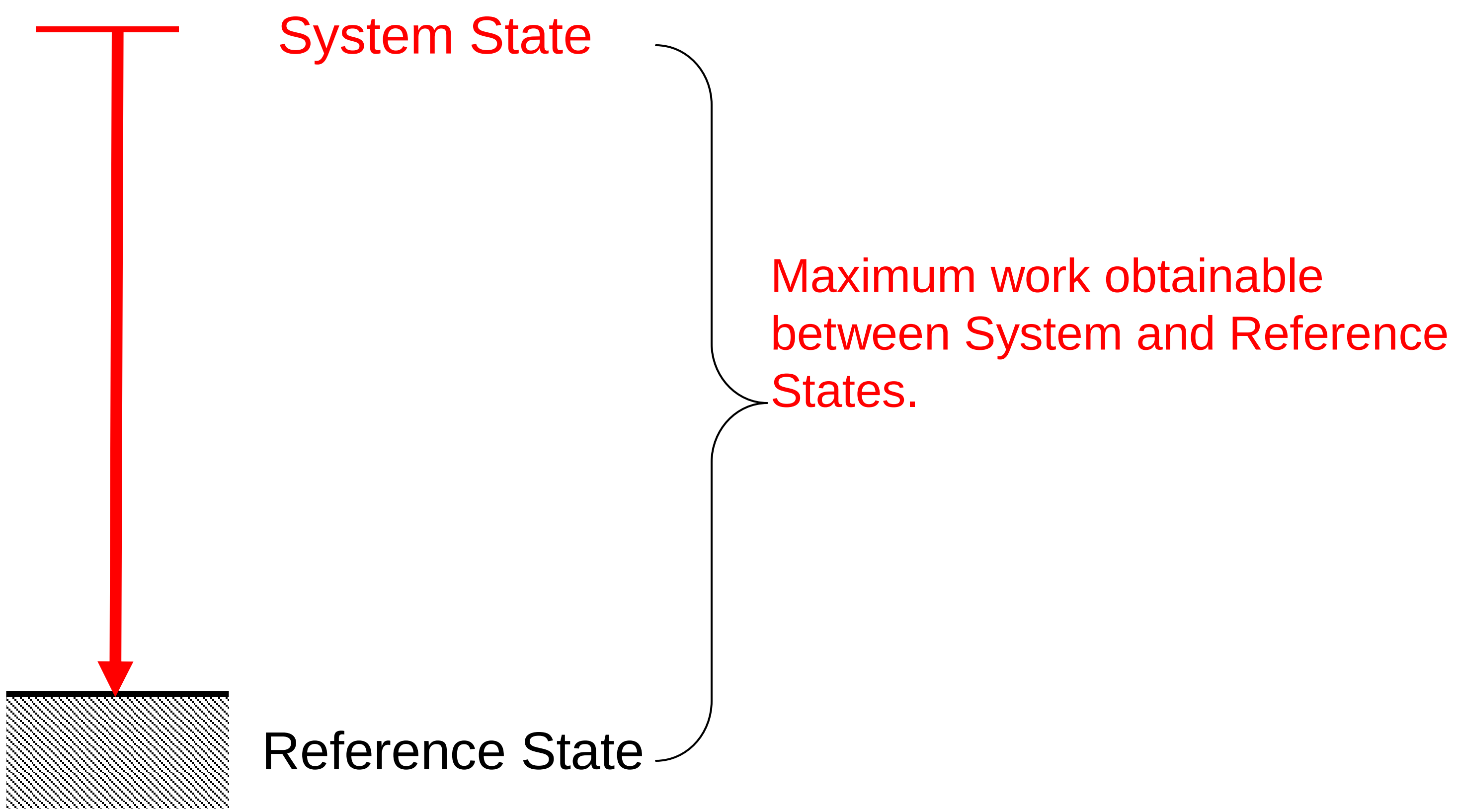
Here all chemical exergy terms (b^{ch}) are at T_o, P_o

Branham et al IEEE ISEE 2008

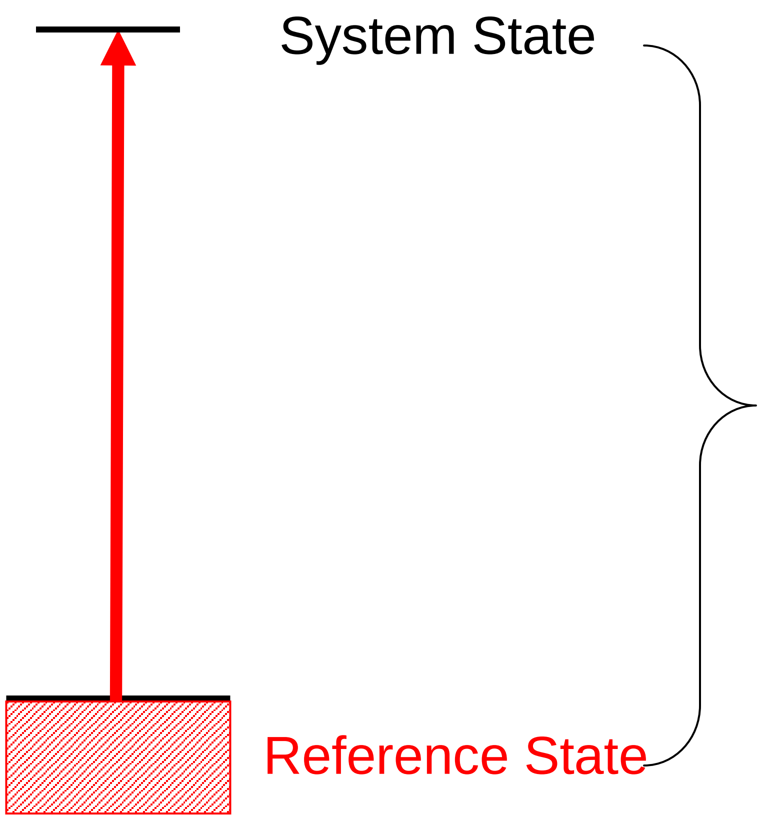
Definition of Exergy "B"

"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

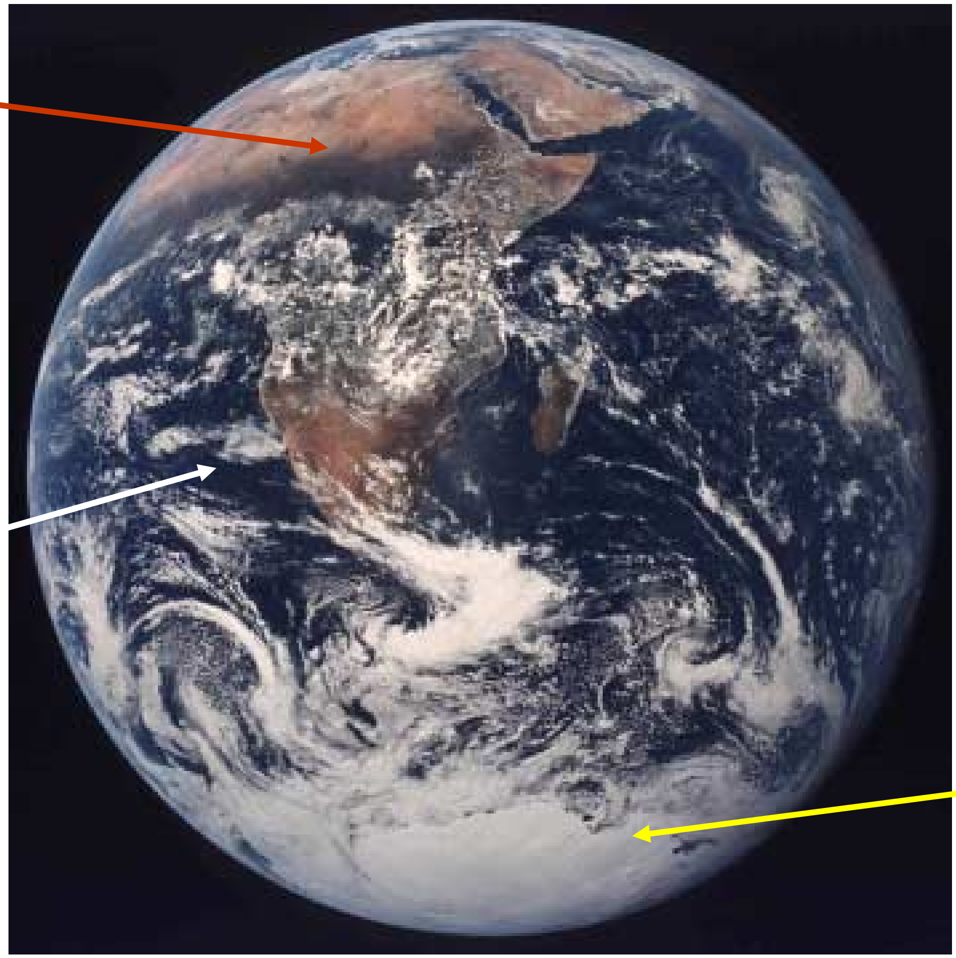

System State
Reference State
Maximum work obtainable between System and Reference States.

Exergy



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

Chemical Properties referenced to the "environment"



COMPOSITION OF AIR

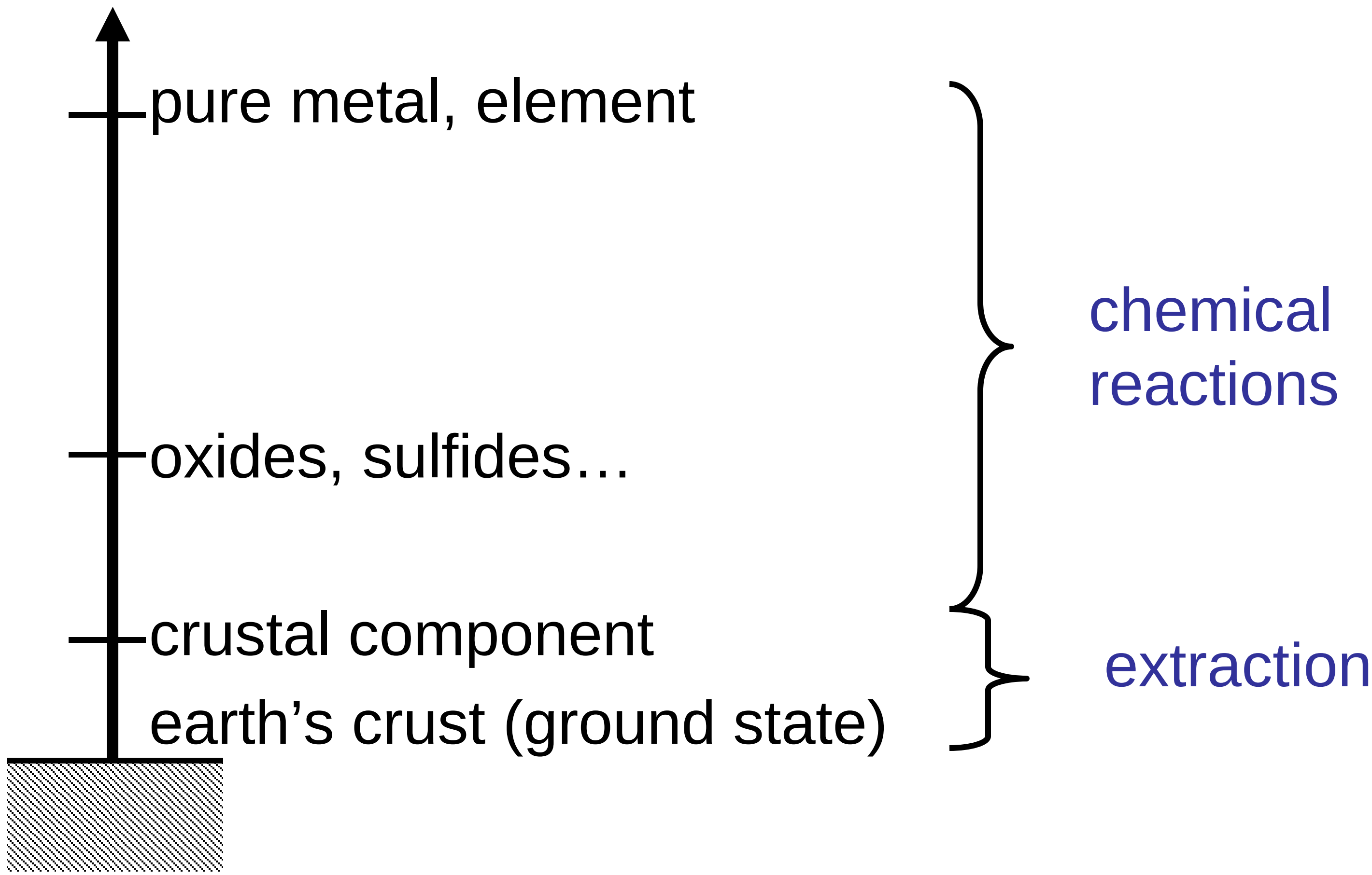
Component of Air	Symbol	Content – %Volume	
Nitrogen	N_2	78.084 percent	99.998%
Oxygen	O_2	20.947 percent	
Argon	Ar	0.934 percent	
Carbon dioxide	CO_2	0.033 percent	
Neon	Ne	18.2 parts/million	
Helium	He	5.2 parts/million	
Krypton	Kr	1.1 parts/million	
Sulfur dioxide	SO_2	1.0 parts/million	
Methane	CH_4	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.

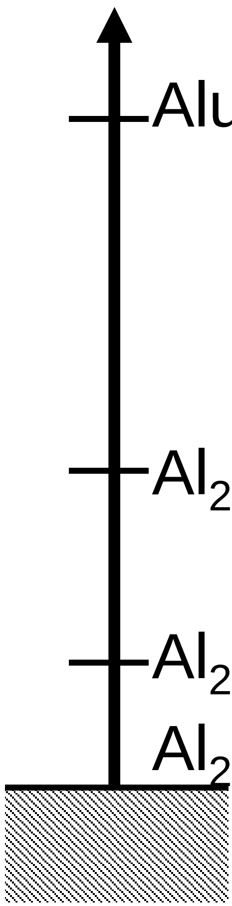
T_o = 298.2 K, P_o = 101.3 kPA

gutowski@mit.edu

Exergy Reference System

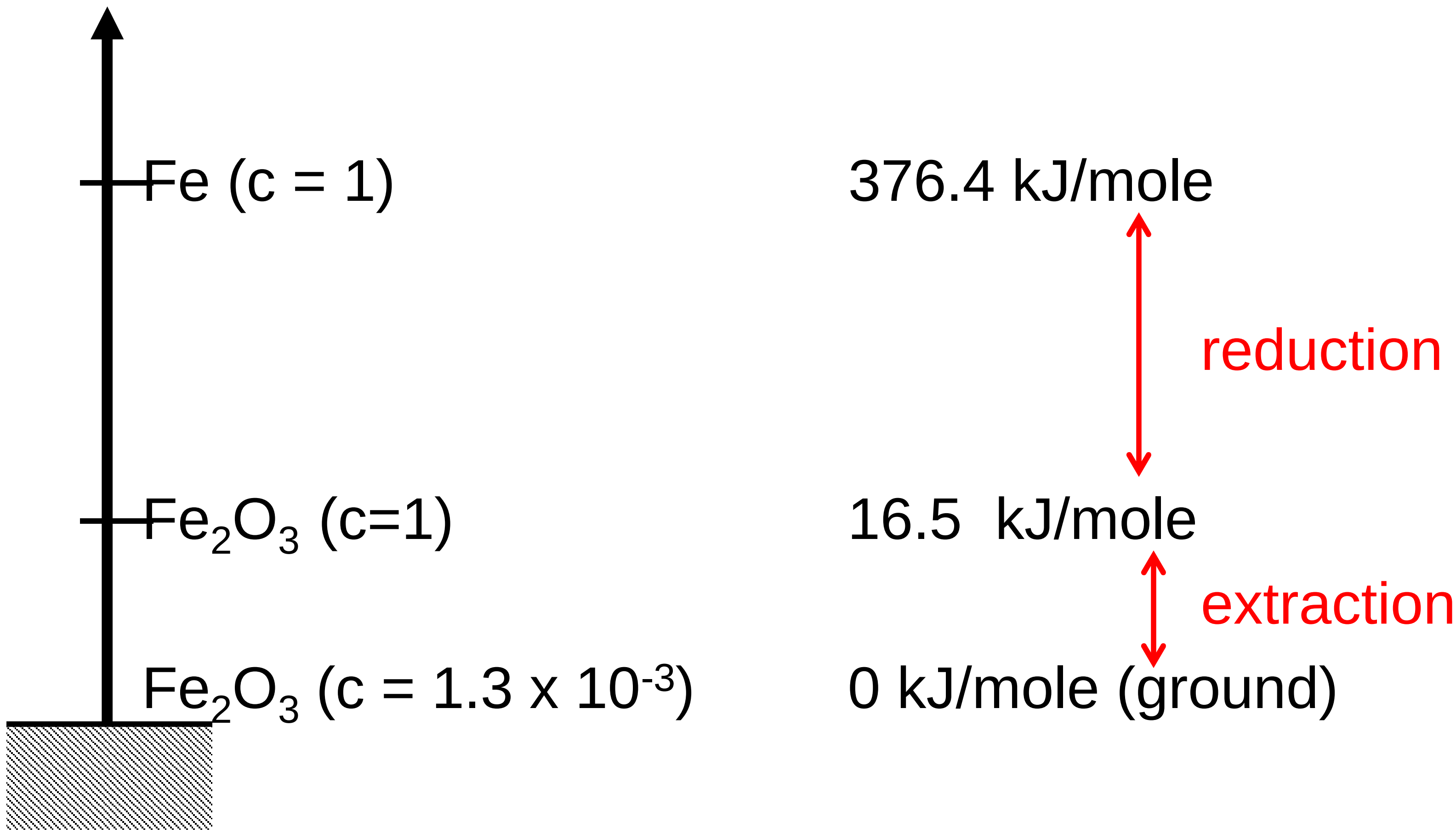


Exergy Reference System

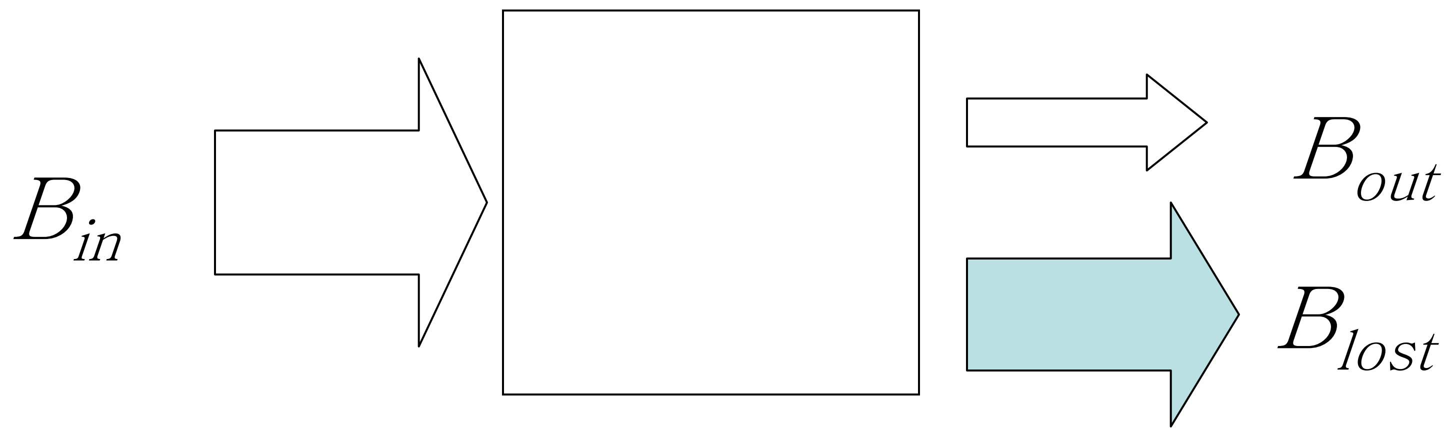


Aluminum (c=1)	888.4 kJ/mole
Al_2O_3 (c=1)	200.4 kJ/mole
Al_2SiO_5 (c=1)	15.4kJ/mole
Al_2SiO_5 ($c = 2 \times 10^{-3}$)	0 kJ/mole (ground)

Example; making pure iron from the crust



Exergy Accounting



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

Chemical Reactions

stoichiometric mass balance

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

exergy "balance"

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

where exergy b is given in kJ/mole

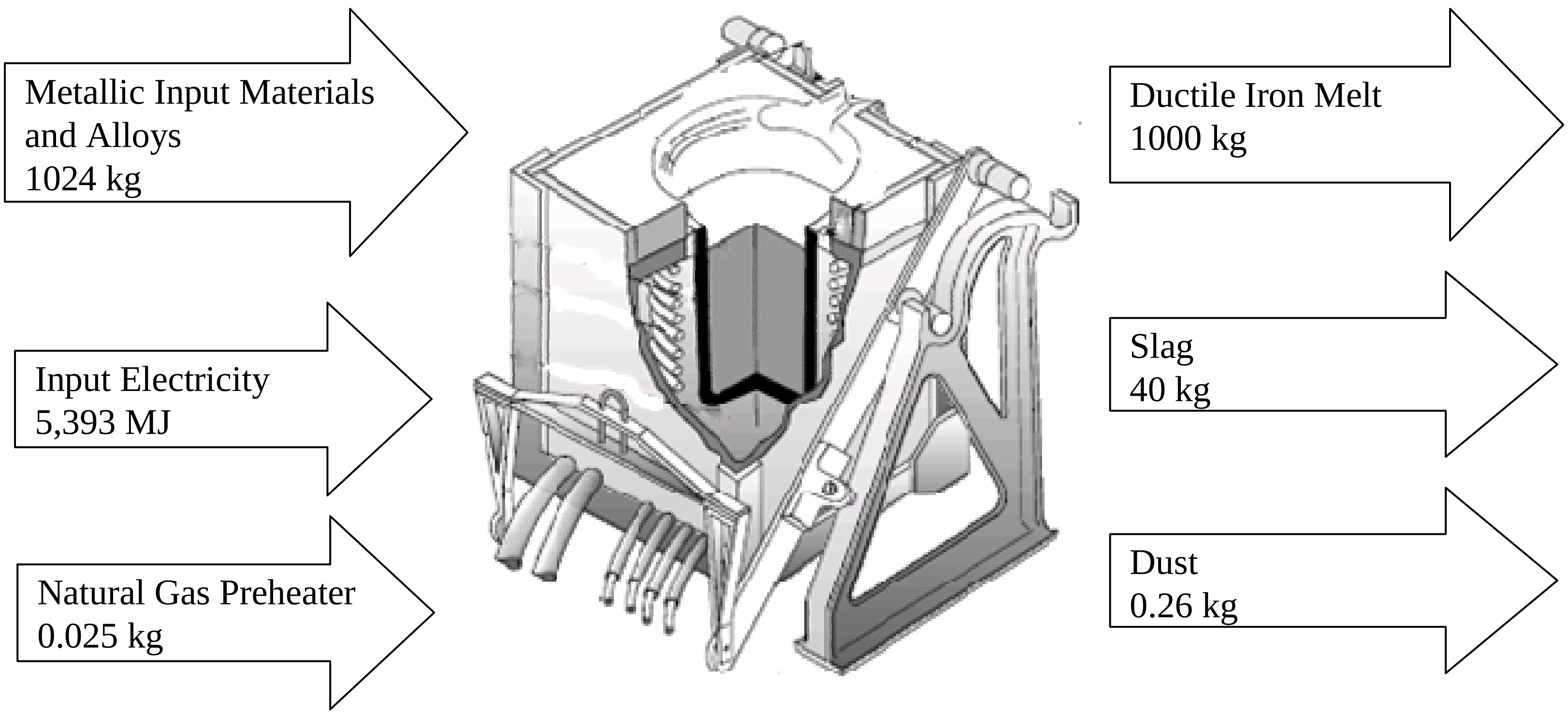
Efficiency Measures

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

$$\eta_{II} = \frac{W_{\min}}{B_{in}}$$

Batch Induction Melter Inputs and Outputs

Ductile Iron – Batch Electric Induction Exergy Analysis



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

*Batch Induction Melter Exergy Analysis**

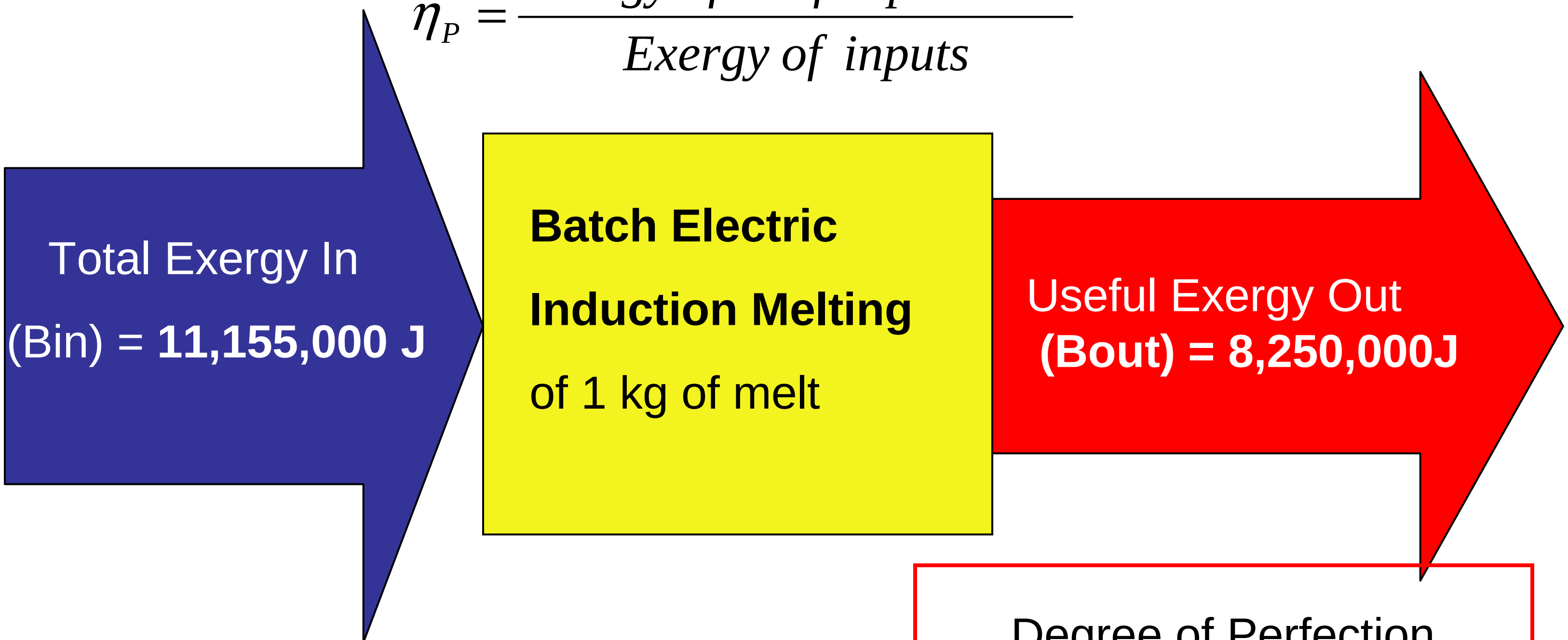
Ductile Iron Batch Electric Induction Melting

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

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



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

Chemical Vapor Deposition

CVD Chemical Inputs

TABLE I USG CVD PROCESS MATERIAL INVENTORY

Chemicals (g/wafer)	In	Out	Post-POU Abatement
CH_4	69.41	-	0.04
NF_3	31.06	2.37	0.09
F_2	-	17.34	0.06
HF	-	0.03	-
SiF_4	-	8.82	0.01
CO	-	-	0.16
NO	-	-	1.25
NO_2	-	-	0.06
SiH_4	0.95	0.23	0.23
O_2	0.49	0.49	0.49
Ar	0.34	0.34	0.34
utility N_2	196.90	196.90	196.90

- Below detection limits

Boyd, Dornfeld
Krishnan, IEEE
ISEE 2006

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

gutowski@mit.edu

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

Advantages and Disadvantages of Exergy Accounting

- Aggregated measure
- Not conserved
- Rigorous framework,
- Utilized in optimization and accounting, but
- Esoteric sounding
- In some cases, First Law will do fine

Most of these results can be found

- on our website:

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

- Branham, Matthew, Timothy Gutowski, Alissa Jones, Dusan Sekulic, "A Thermodynamic Framework for Analyzing and Improving Manufacturing Processes", IEEE, ISEE, San Francisco May 19-20, 2008,
- Gutowski, T., J. Dahmus, A. Thiriez, M. Branham, and A. Jones. "A Thermodynamic Characterization of Manufacturing Processes", IEEE, ISEE, Orlando, FL May 7-10, 2007
- Jones, Alissa, "The Industrial Ecology of the Iron Casting Industry" M.S. Thesis, Department of Mechanical Engineering, MIT 2007