



*Introduction to the  
“Exergy” Concept* 

2.83/2.813

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# Readings

1. Ch.2 Thermodynamics Revisited (p 7-13), and
2. Ch 6 Exergy, a Convenient Concept (p 59-62), Jakob de Swaan Arons, 2004
3. Ch 6 Thermodynamic Analysis of Resources Used in Mfg Processes, Gutowski & Sekulic, in TDR 2011
4. Appendix, Tables of Standard Chemical Exergy, Szargut, Morris & Steward, 1988

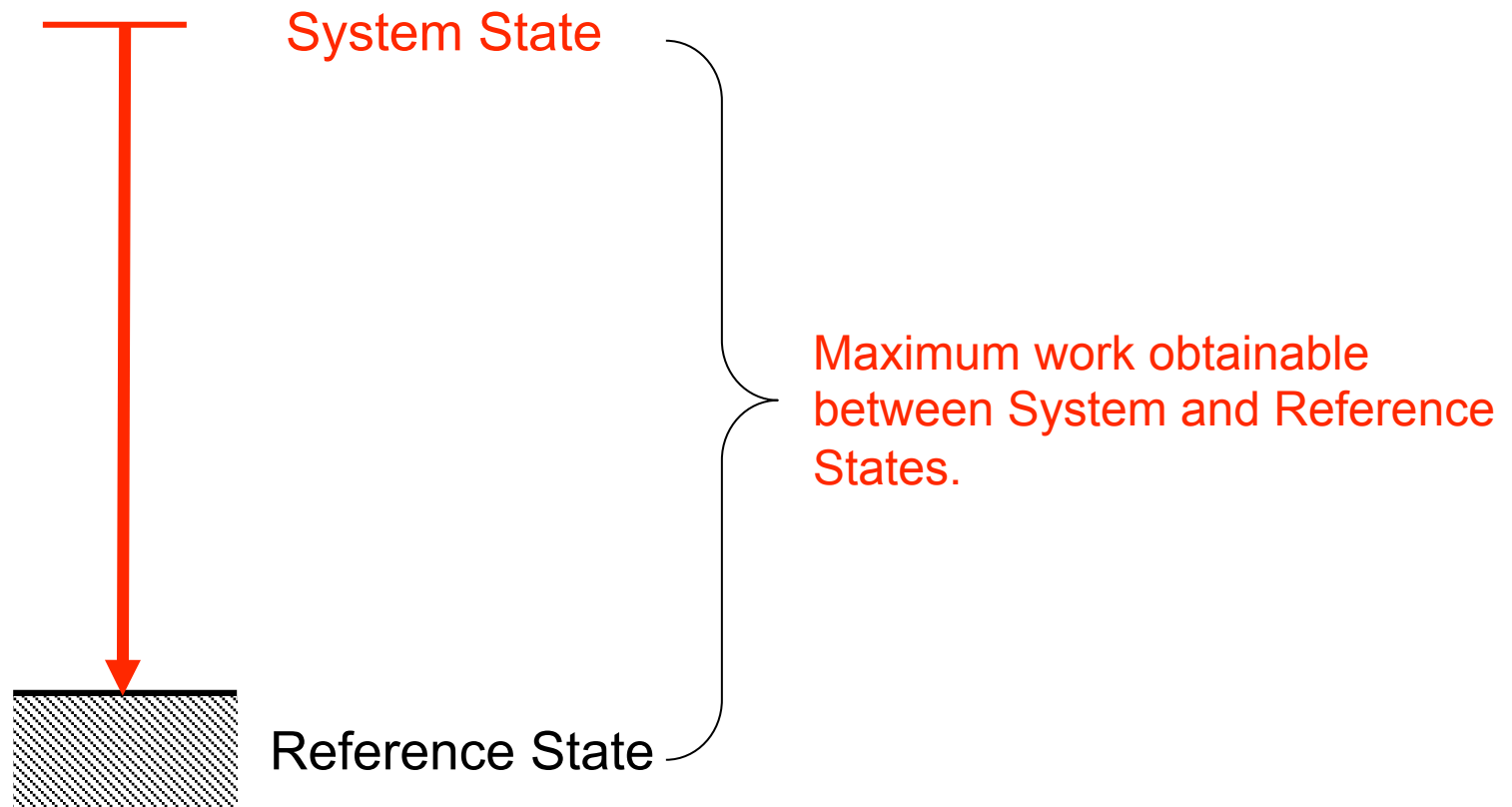
# Exergy Accounting

- Exergy Units: Joules  $J$ , rate in Watts,  $W$
- Exergy symbols:  $B$ ,  $Ex$ ,  $X$ , and  $b$ ,  $e_x$ ,  $x$
- Also called “Availability” by Keenan, 1941 and “Available Energy”,  $\Omega^R$ , by Gyftopoulos and Beretta, 1991

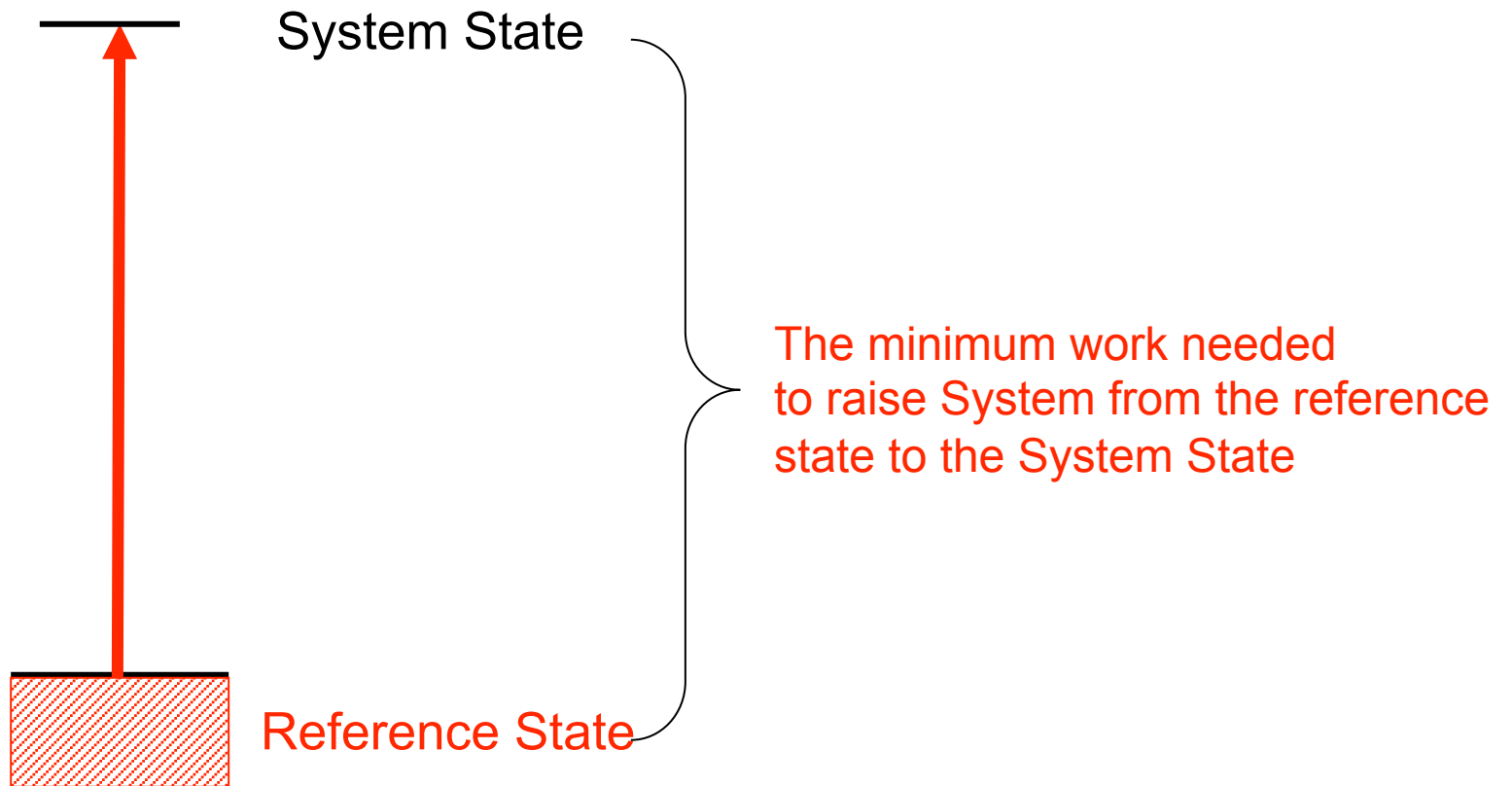
# Definition of Exergy

“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].

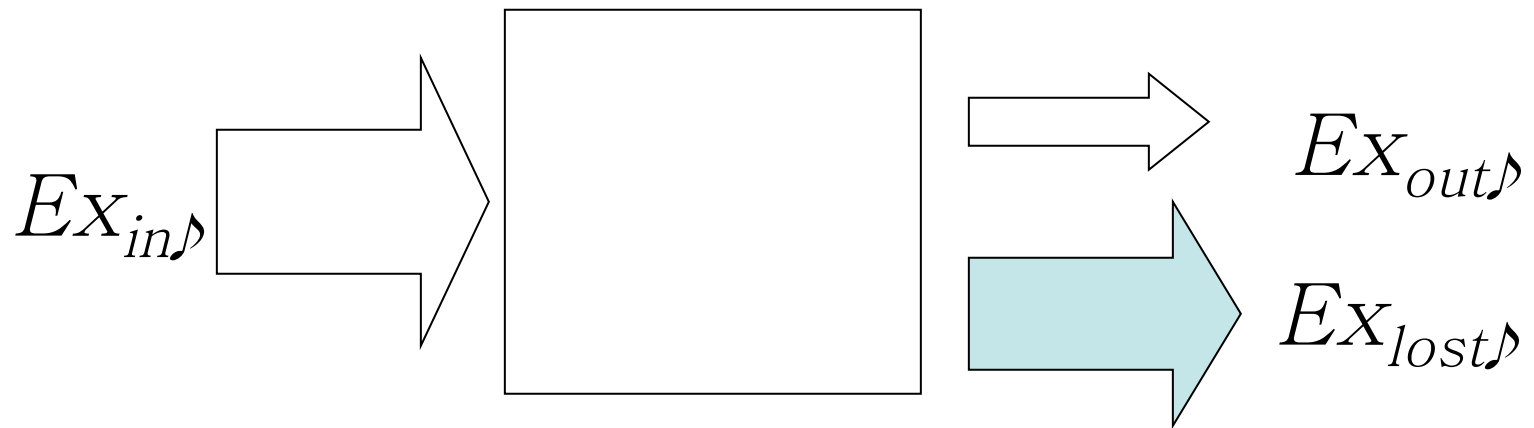
# Exergy



# Exergy



# Aggregate Exergy Accounting



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

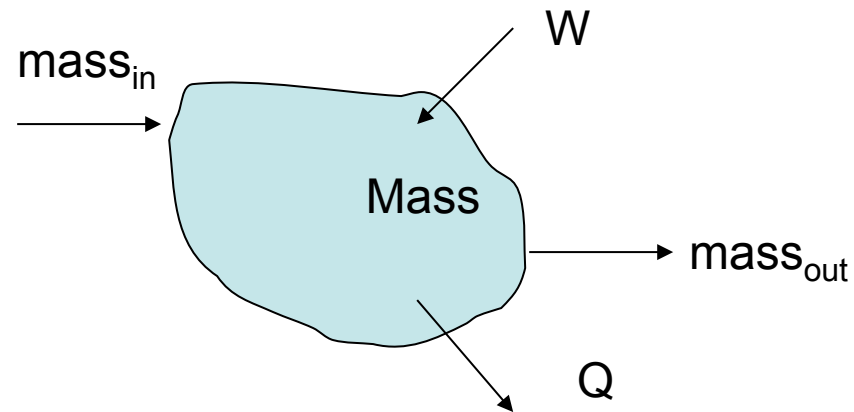
# Thermodynamics Overview

- Systems
- Heat Interactions
- Exergy of heat interaction
- Entropy and Enthalpy
- Physical and Chemical Exergy



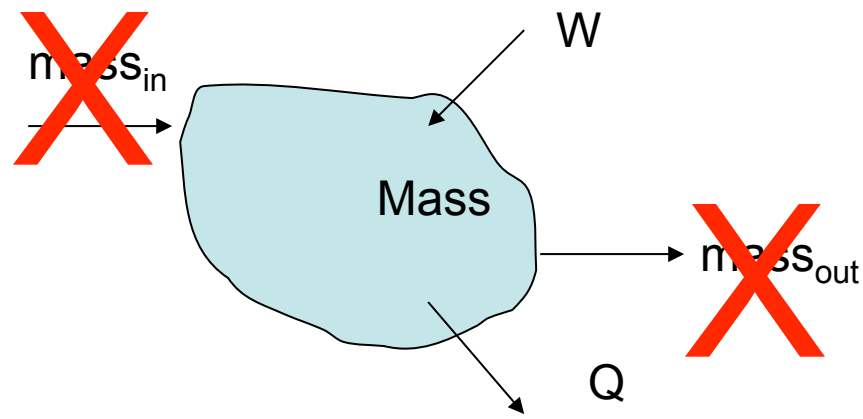
# Open System

Work interaction

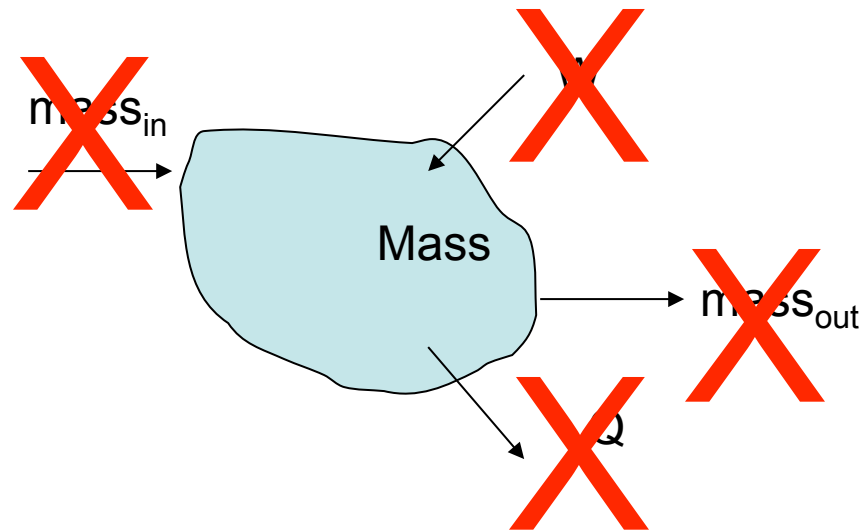


Heat interaction

# Closed System



# Isolated System



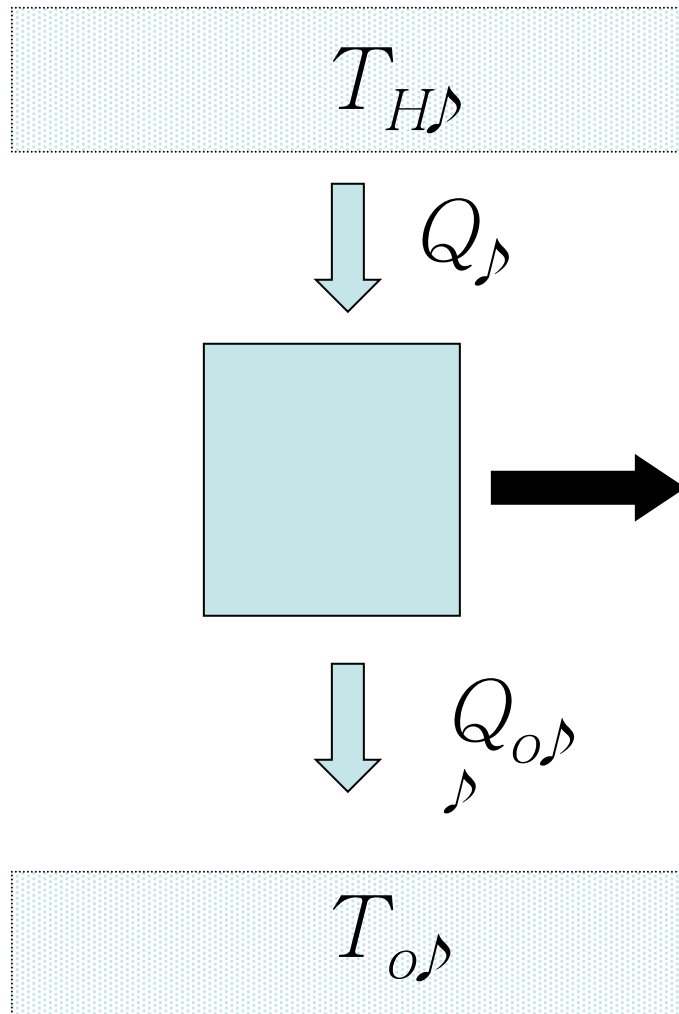
# The 1st Law

$$\Delta U = Q_{in} - W_{out}$$

$$dU = \delta Q_{in} - \delta W_{out}$$

$$\oint dQ - \oint dW = 0$$

# Heat Interaction $Q$



$$W_{out} = Q - Q_o$$

$$\eta = \frac{W_{out}}{Q} = 1 - \frac{Q_o}{Q}$$

# Carnot's "Reversible" Heat Engine

$$\eta_{reversible} = f(T_H, T_L) \quad \frac{Q_{out}}{Q_{in}} = \frac{T_L}{T_H}$$

$$\eta = 1 - \frac{T_L}{T_H}$$

# *Maximum Work Output*

$$W_{out}^{\max} = Q_{in} \left(1 - \frac{T_L}{T_H}\right)$$

- $Q_{in}$  is at  $T_H$ , let  $T_L$  be  $T_{ref}$  or  $T_o$
- This gives the “available energy” of a heat interaction at  $T_H$  in reference  $T_o$ .
- Work and Heat are no longer equivalent!

# *Exergy “Ex” of Heat Interaction*

$$E_X^Q = Q\left(1 - \frac{T_o}{T}\right)$$

- Exergy, “Ex” is the available energy w.r.t. a reference environment,  $T_o$ , and  $P_o$ ...
- $Ex(work) = W$ ;       $Ex(heat) = Q(1 - T_o/T)$



# Availability♪

“The **First Law** states that in every cyclic process either work is converted into heat or heat is converted into work. In this sense it **makes no distinction between work and heat** except to indicate a means of measuring each in terms of equivalent units. Once this technique of measurement is established, work and heat become entirely equivalent for all applications of the First Law.”

# Availability

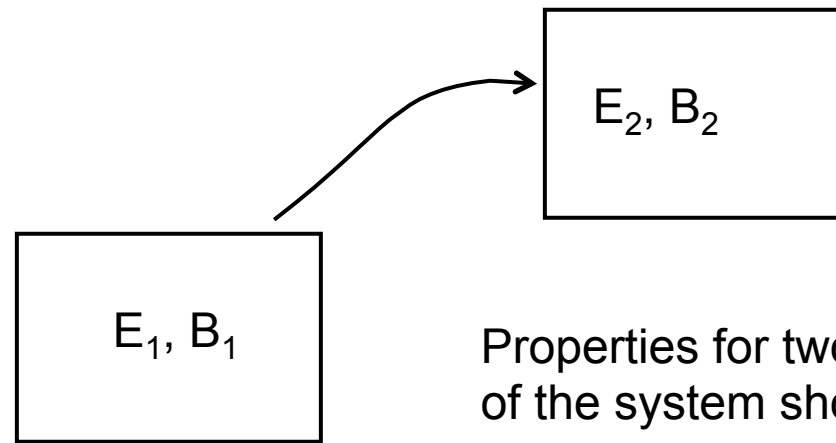
- “The **Second Law**, on the other hand, marks the distinction between these two quantities by stating that heat from a single source whose temperature is uniform cannot be completely converted into work in any cyclic process, whereas work from a single source can always be completely converted into heat.”

# Availability♪

“The efforts of the engineer are very largely directed toward the control of processes so as to produce the maximum amount of work, or so as to consume the minimum amount of it. The success of these efforts can be measured by comparing the amount of work produced in a given process with the **maximum possible amount of work** that could be produced in the course of a *change of state* identical with that which occurs in the process.”

Keenan, 1941

# Energy, $E$ and Exergy, $B = Ex$



Properties for two different states of the system shown by the boxes. This change may come about due to spontaneous changes or due to heat or work interaction, or mass transfer.

$$B_1 - B_2 = E_1 - E_2 \quad \text{Reversible process}$$

$$B_1 - B_2 > E_1 - E_2 \quad \text{Irreversible process}$$

Ref: Gyftopoulos and Beretta

# Define Entropy

$$S_1 = S_o + \frac{1}{C_R} [(E_1 - E_o) - (B_1 - B_o)]$$

- They show  $C_R = T_R = T_o$
- Entropy is a Property
- Entropy is a measure of something lost

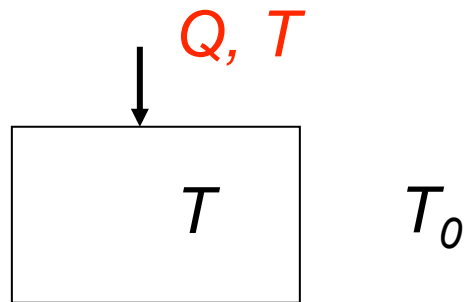
Ref: Gyftopoulos and Beretta

# Entropy Difference

$$S_2 - S_1 = \frac{1}{C_R} \left[ (E_2 - E_1) - (B_2 - B_1) \right]$$

- $\Delta S = 0$ , reversible process
- $\Delta S > 0$ , irreversible process

# Example, Heat Interaction



$$E_2 = E_1 + Q \text{♪}$$

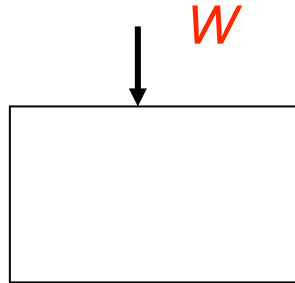
$$B_2 = B_1 + Q(1 - T_0/T) \text{♪}$$

$$\Delta S = (1/T_0)(Q - Q + Q(T_0/T)) = Q/T \text{♪}$$

♪

$$\Delta S = Q/T \text{♪}$$

# Example, Work Interaction



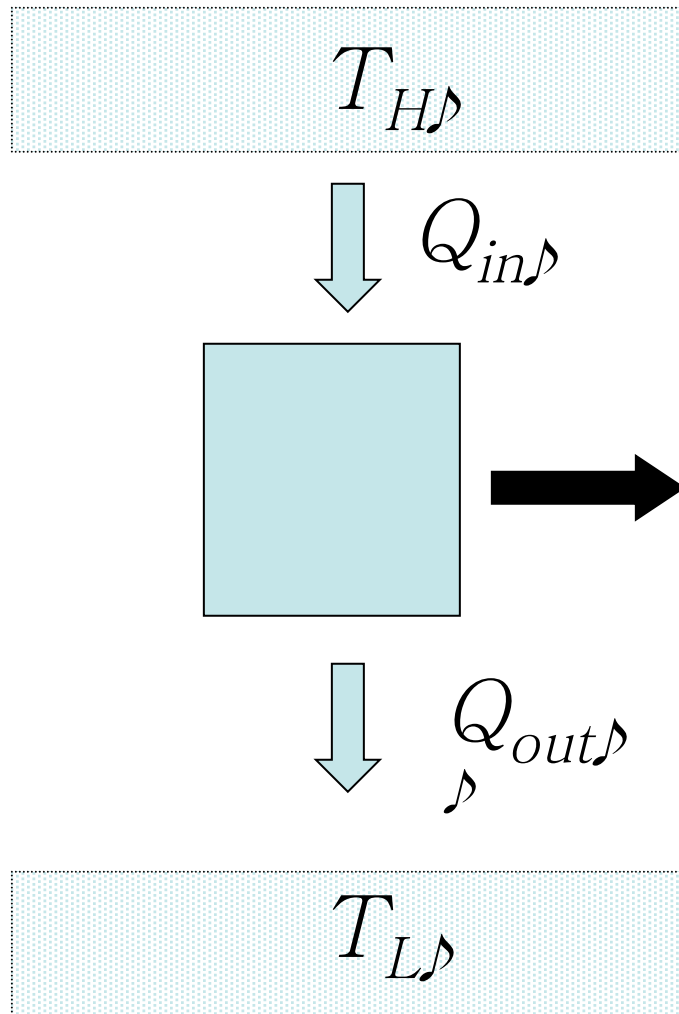
$$E_2 = E_1 + W$$

$$B_2 = B_1 + W$$

$$\Delta S = (W - W) = 0$$



# Homeworks 1 & 2



1. Calculate the entropy change for a reversible heat engine, and
2. Calculate the entropy loss for a reversible heat engine.

Use the results given in this Presentation.

# Answers for 1 & 2

Consider the process in two stages; 1) you transfer heat in, and 2) You transfer heat and work out. Use the result from Carnot to Show that the change in entropy is zero. This leads to the result that The exergy lost is also zero.

$$\Delta S = S_2 - S_1 = \frac{1}{T_o} \left[ (E_2 - E_1) - (B_2 - B_1) \right] = \frac{Q_L}{T_L} - \frac{Q_H}{T_H}$$

$$B_{lost} = Q_H - Q_L + T_o \Delta S - W$$

# Properties or State Variables

- T = temperature
- P = pressure
- V = volume
- U = internal energy
- E = energy
- B = exergy
- H = enthalpy ( $H = U + PV$ )
- S = entropy

intensive variables

extensive  
and  
intensive  
variables

## State Variables

$$\oint dU = 0 \qquad \int_1^2 d\phi = \phi_2 - \phi_1$$

$$\oint \frac{dQ}{T} = 0 \qquad \oint d(U + PV) = 0$$

# Enthalpy $H=U+ PV$

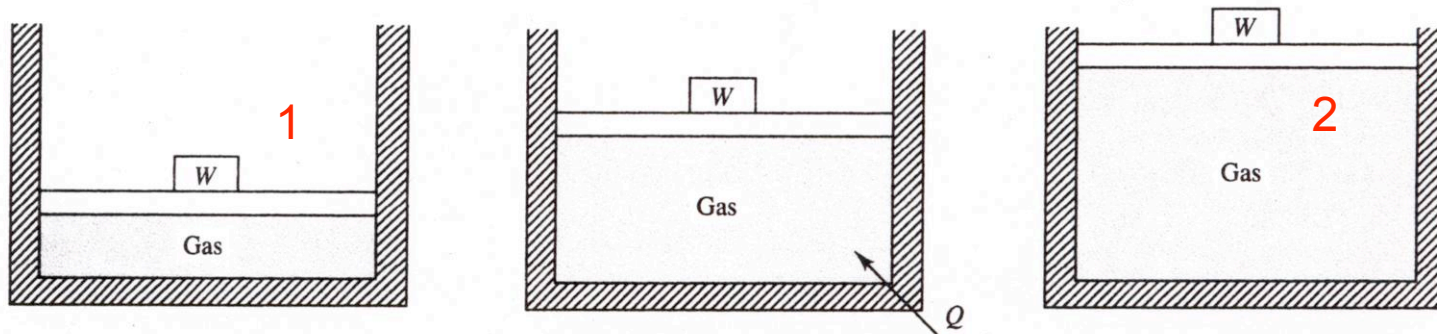


Fig. 4-4 Constant-Pressure Heat Addition

Here the Work done is

$$W = P(V_2 - V_1)$$

The First Law can be written as

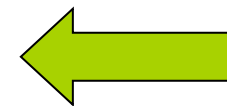
$$Q = (U+PV)_2 - (U + PV)_1$$

The quantity in parenthesis is Enthalpy

$$H = U + PV$$

The First Law can be written as

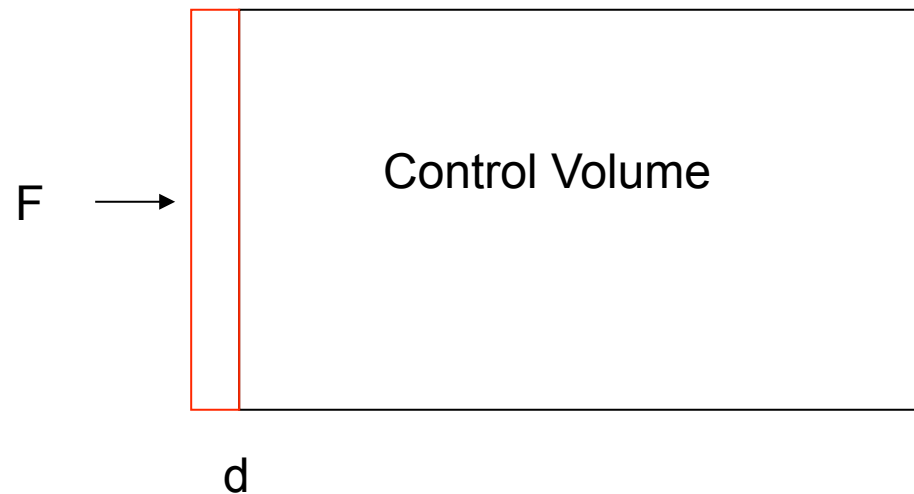
$$Q_{in} = \Delta H$$



**Constant Pressure Equilibrium Process**

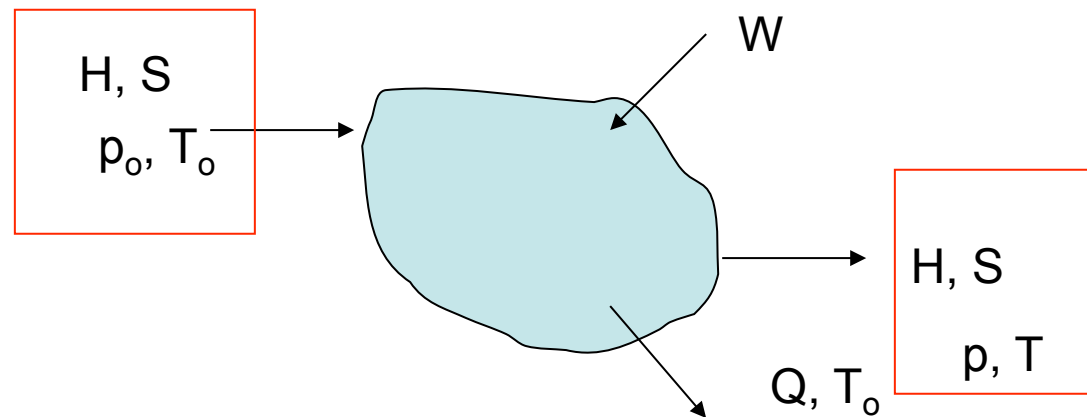
# For Flow System Energy

$$U + P\nu + \frac{1}{2}mV^2 + mgz = H + \frac{1}{2}mV^2 + mgz$$



$$W_{boundary} = Fd = P\nu$$

# *Open System with $H, S$*



Consider the Work to bring the system from the reference environment at standard conditions,  $T_o, p_o$  to the state at  $T, p$

*See Ch 6 de Swaan Arons*

From EQ 1 & 2(Ch 6), de Swaan Arons♪

$$\dot{H}_{in} - \dot{H}_{out} - \dot{Q}_{out} + \dot{W}_{in} = 0$$

$$\dot{S}_{in} - \dot{S}_{out} - \frac{\dot{Q}_{out}}{T_o} + \dot{S}_{generated} = 0$$

$$\dot{W} = \Delta\dot{H} - T_o\Delta\dot{S} + T_o\dot{S}_{generated}$$

Steady State Work to bring system from  $P_o, T_o$  to  $P, T$



# Minimum Work = Exergy♪

$$\begin{aligned}W_{\min} &= \frac{\dot{W}_{rev}}{\dot{m}} = \Delta H - T_o \Delta S \\ &= (H_{p,T} - H_{p_o,T_o}) - T_o (S_{p,T} - S_{p_o,T_o})\end{aligned}$$

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

$$W_{\min} = \frac{\dot{W}_{rev}}{\dot{m}} = B_{out} - B_{in}$$

# Lost Work & Lost Exergy

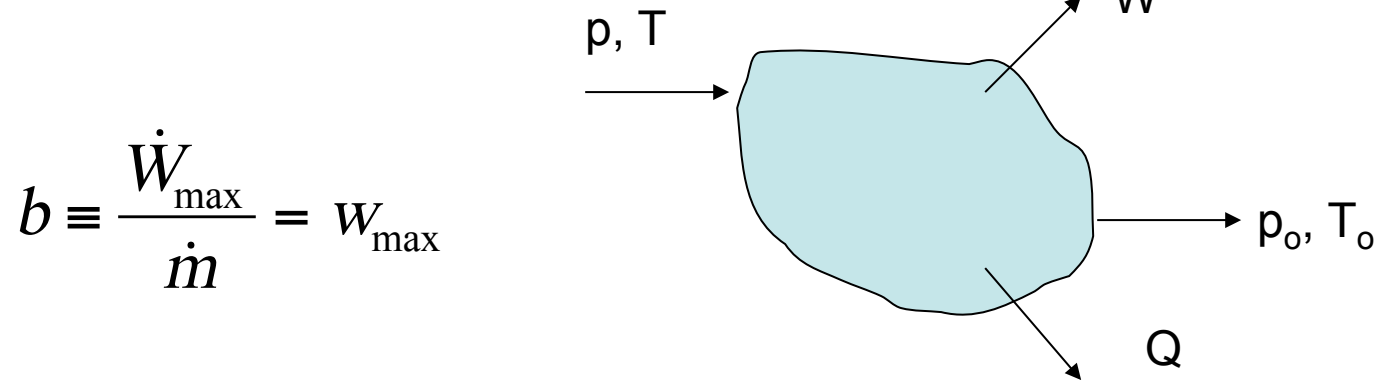
Recall:

$$\dot{W} = \dot{B}_{out} - \dot{B}_{in} + T_o \dot{S}_{generated}$$

Let:  $\dot{W} = \dot{W}_{min} + \dot{W}_{lost}$  then

$$\dot{W}_{lost} = \dot{B}_{lost} = T_o \dot{S}_{generated}$$

Exergy also is ...♪



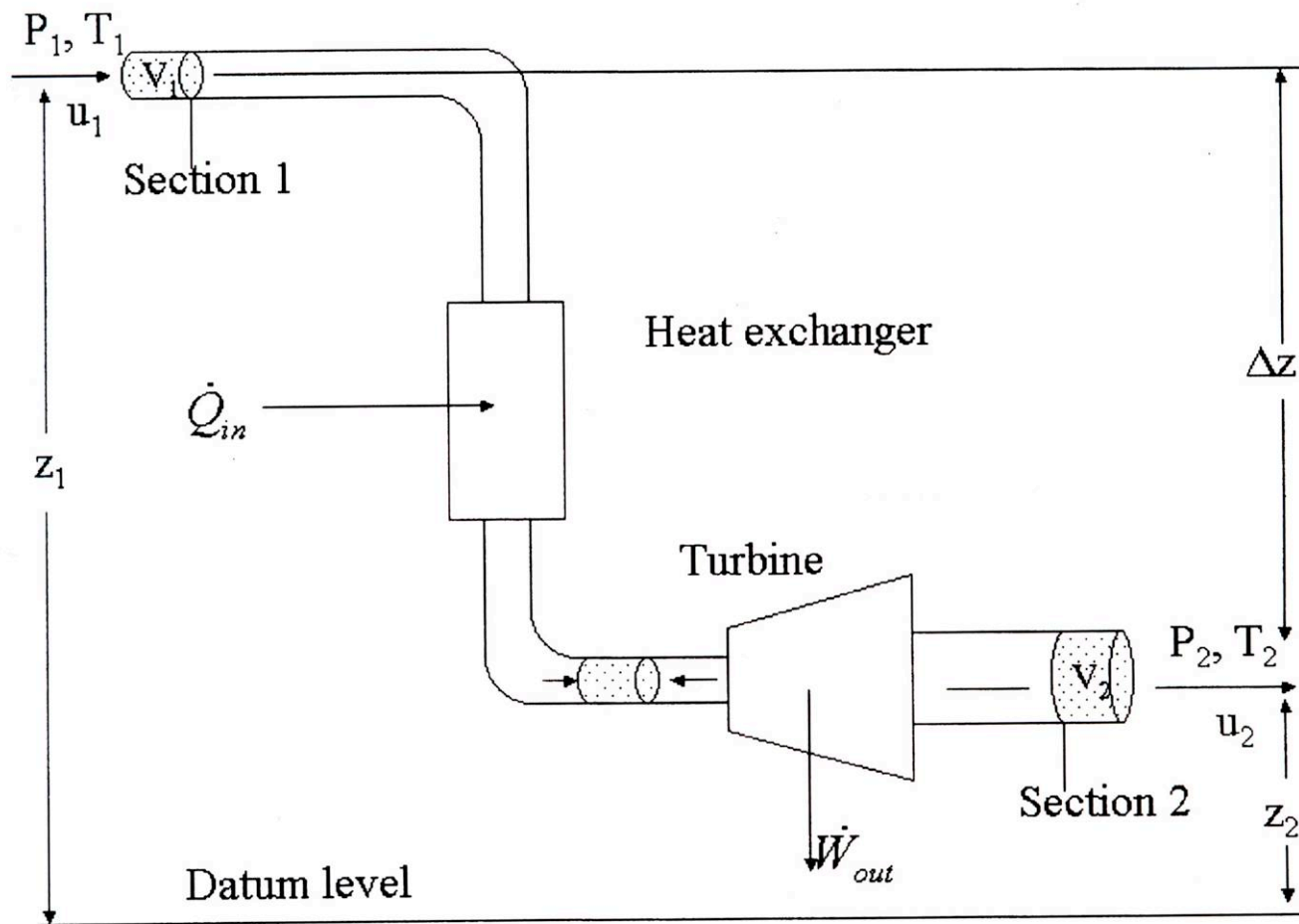
$$b \equiv \frac{\dot{W}_{\max}}{\dot{m}} = W_{\max}$$

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

... the maximum amount of work that can be obtained from a system in reference to the environment at standard conditions,  $T_o$ ,  $P_o$

Standard ref. values  $T_o = 298.2^\circ K$ ,  $P_o = 101.3 kPa$

# Open flow system



**Figure 1** Changes in steady-state flow.

# First Law for a Flow System

$$\begin{aligned} \left( \frac{dU}{dt} \right)_{cv} &= \sum_{in} \dot{m}_i \left( h_i + \frac{u_i^2}{2} + gz_i \right) \\ &\quad - \sum_{out} \dot{m}_j \left( h_j + \frac{u_j^2}{2} + gz_j \right) \\ &\quad + \sum \dot{Q}_{in} - \sum \dot{Q}_{out} + \sum \dot{W}_{sh,in} - \sum \dot{W}_{sh,out} \end{aligned}$$

$$\dot{m} \left( \Delta H + \frac{\Delta u^2}{2} + g\Delta z \right) + \dot{Q}_{in} - \dot{W}_{out} = 0$$

**EQ 1**

one stream steady state

## Second Law for a Flow System

$$\left(\frac{dS}{dt}\right)_{cv} = \sum_{in} \dot{m}_i S_i - \sum_{out} \dot{m}_j S_j + \sum_{in} \int \frac{\delta \dot{Q}_k}{T} - \sum_{out} \int \frac{\delta \dot{Q}_1}{T} + \dot{S}_{generated}$$

$$\dot{m}\Delta S + \frac{\dot{Q}_{surr}}{T} + \dot{S}_{generated} = 0$$

EQ 2

one stream steady state

From EQ 1 & 2

$$\dot{m} \left( \Delta H + \frac{\Delta u^2}{2} + g\Delta z \right) + \dot{Q} - \dot{W}_{out} = 0$$

$$\dot{m}\Delta S + \frac{\dot{Q}}{T_0} + \dot{S}_{generated} = 0$$

$$\dot{W}_{rev} = \dot{m} \left( \Delta H + \frac{\Delta u^2}{2} + g\Delta z \right) - \dot{m}T_0\Delta S$$

# *Physical and Chemical Exergy*

- $B = B^{ph} + B^{ch}$
- $B^{ph}(T=T_o, p=p_o, \mu = \mu^* \neq \mu_o) = 0$   
– this is the “restricted dead state”
- $B^{ch}(\mu^* = \mu_o) = 0$
- when  $B = B^{ph} + B^{ch} = 0$   
– this is the “dead state”



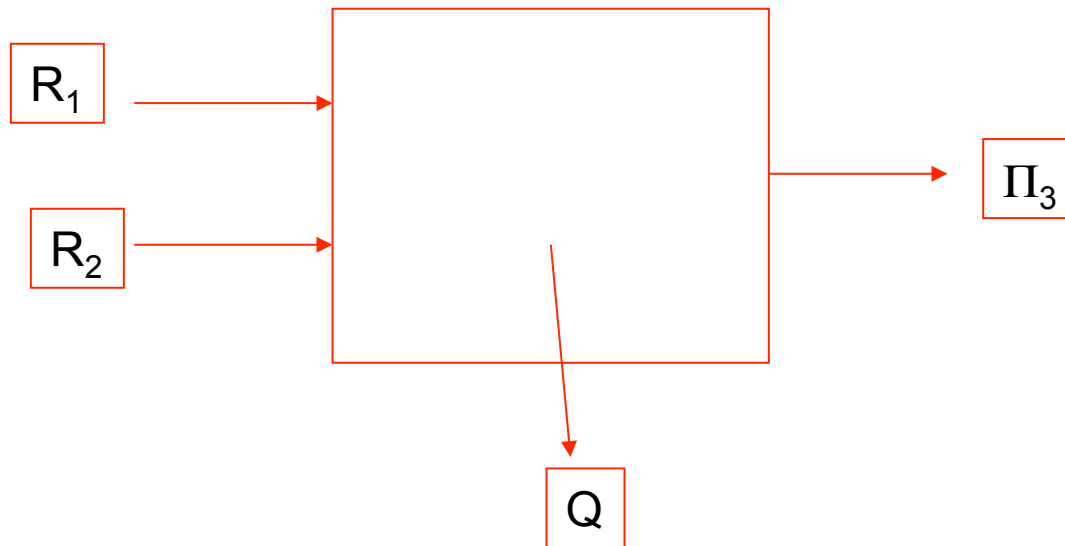
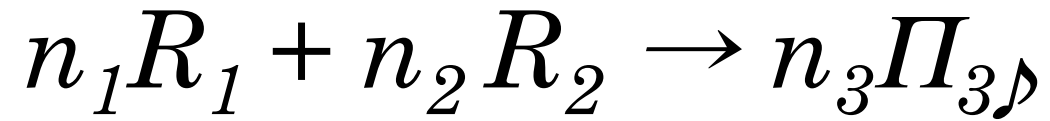
# Thank you Jan Szargut

## APPENDIX 1. STANDARD CHEMICAL EXERGY ( $T_n = 298.15\text{ K}$ , $p_n = 101.325\text{ kPa}$ )

Source: Szargut, J., Egzergia. Poradnik obliczania i stosowania, Wydawnictwo Politechniki Szlaskiej, Gliwice 2007.

Substance	State	Molecular mass	Enthalpy of devaluation	Standard chemical exergy
		M, kg/kmol	$D^\circ$ , kJ/mol	$e_{x,ch}^\circ$ , kJ/mol
Al	s	26.9815	930.9	795.7
Al <sub>4</sub> C <sub>3</sub>	s	143.959	4694.51	4216.2
AlCl <sub>3</sub>	s	133.3405	467.18	352.2
Al <sub>2</sub> O <sub>3</sub>	s. $\alpha$ corundum	101.9612	185.69	15.0
Al <sub>2</sub> O <sub>3</sub> •H <sub>2</sub> O	s. boermit	119.9765	128.35	9.4
Al <sub>2</sub> O <sub>3</sub> •3H <sub>2</sub> O	s. gibbsite	156.0072	24.13	24.1
Al <sub>2</sub> S <sub>3</sub>	s	150.155	3313.81	2705.3
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	s	342.148	596.80	344.3
Al <sub>2</sub> SiO <sub>5</sub>	s. andalusite	162.046	28.03	9.2
Al <sub>2</sub> SiO <sub>5</sub>	s. kyanite	162.046	25.94	12.9
Al <sub>2</sub> SiO <sub>5</sub>	s. sillimanite	162.046	0	15.3
Al <sub>2</sub> SiO <sub>5</sub> •(OH) <sub>4</sub>	s. kaolinite	258.1615	68.25	12.0
3Al <sub>2</sub> O <sub>3</sub> •2SiO <sub>2</sub>	s. mullite	426.0536	630.11	63.2

*Chemical Reaction, at  $T_o, p_o$*



# Chemical Reactions

stoichiometric mass balance

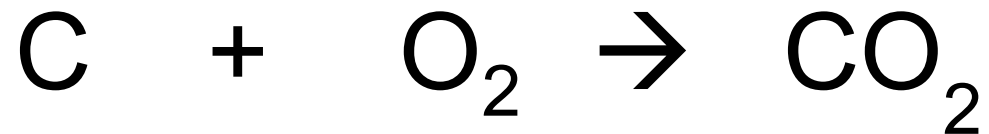


exergy "balance"

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

where exergy  $b$  is given in kJ/mole

# Example: Burning Carbon♪



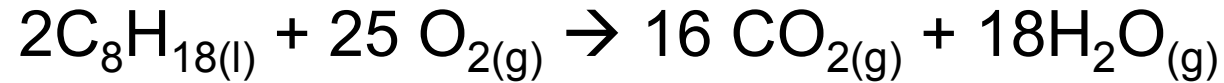
$$\begin{array}{rcccccc} B_{\text{C}} & + & B_{\text{O}_2} & - & B_{\text{CO}_2} & = & \Delta B \\ 410.3 \frac{\text{kJ}}{\text{mol}} & + & 3.97 \frac{\text{kJ}}{\text{mol}} & - & 19.9 \frac{\text{kJ}}{\text{mol}} & = & 394.4 \text{kJ} \end{array}$$

The maximum work you can get out of one mol of carbon is

$$\frac{394.4 \text{ kJ}}{\text{mol of carbon}} = 32.9 \frac{\text{MJ}}{\text{kg}}$$

These exergy values come from Szargut's Appendix Tables

# Burning Octane



$$2(5413.1) + 25(3.97) - 16(19.87) - 18(9.5) = \Delta B$$

$$\Delta B = 10,436.53 \text{ kJ/2 mols of octane}$$

$$\frac{10,436.53}{(2[(8 \times 12) + 18]= 228\text{g})} = \frac{45.8 \text{ MJ}}{\text{kg}}$$

Note:  $\Delta B = -\Delta G_f^\circ = \Delta H - T_o\Delta S \approx \text{LHV}$

TABLE 31.7. Values of enthalpy, Gibbs free energy, and entropy of combustion of fuels at standard temperature,  $T_0 = 25^\circ\text{C}$ , and pressure,  $p_0 = 1 \text{ atm}$ .<sup>a</sup>

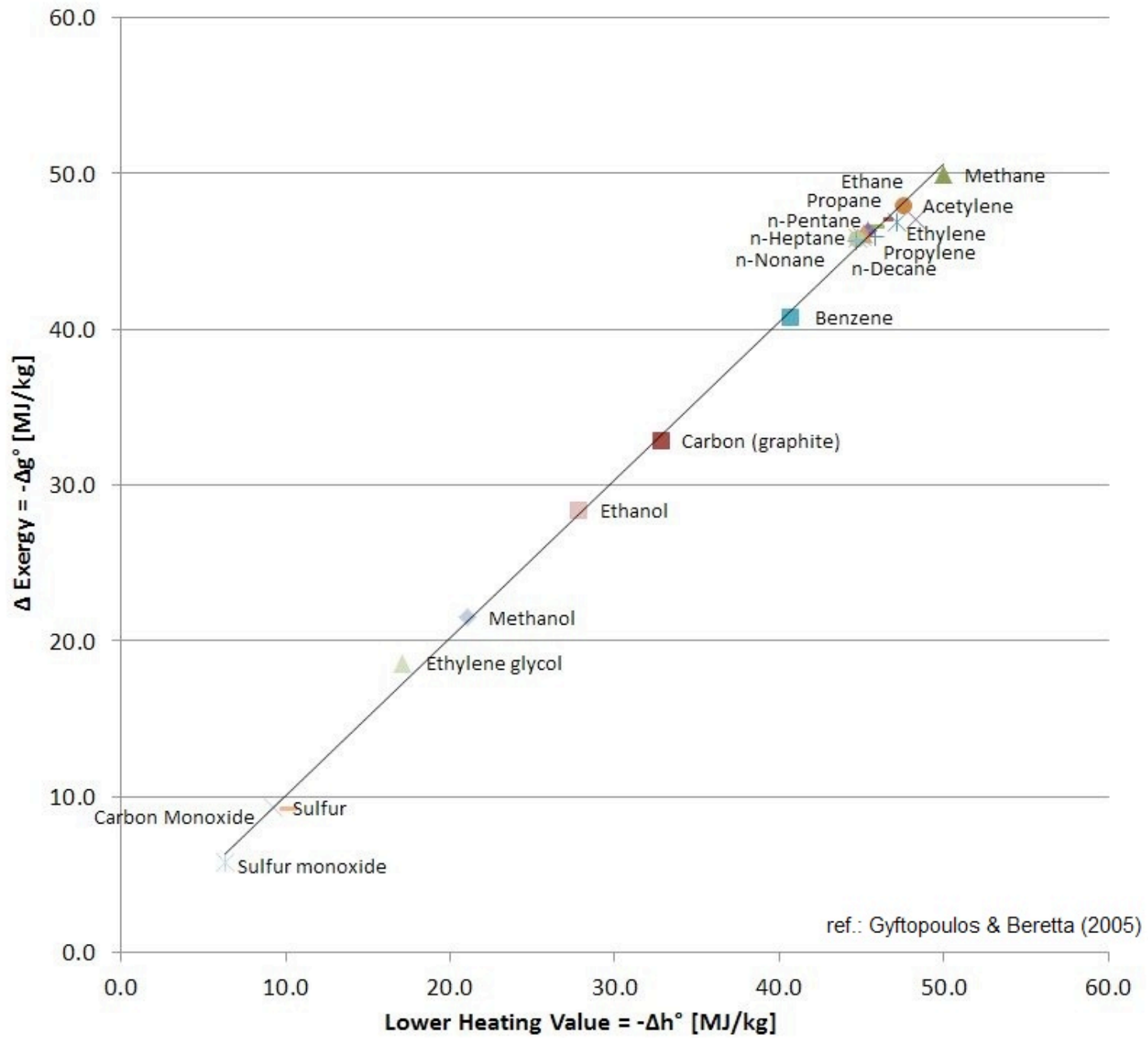
Fuel	Formula	$M$	$\Delta h^\circ$	$\Delta g^\circ$	$\Delta s^\circ$	$\frac{\Delta h^\circ - \Delta g^\circ}{\Delta g^\circ}$
		$\frac{\text{kg}}{\text{kmol}}$	$\frac{\text{MJ}}{\text{kg}}$	$\frac{\text{MJ}}{\text{kg}}$	$\frac{\text{kJ}}{\text{kg K}}$	%
Hydrogen	H <sub>2</sub>	2.016	-120.0	-113.5	-22.0	+5.8
Carbon (graphite)	C	12.011	-32.8	-32.9	0.2	-0.2
Methane	CH <sub>4</sub>	16.043	-50.0	-49.9	-0.3	+0.2
Acetylene	C <sub>2</sub> H <sub>2</sub>	26.038	-48.3	-47.1	-3.7	+2.4
Ethylene	C <sub>2</sub> H <sub>4</sub>	28.054	-47.2	-46.9	-1.1	+0.7
Ethane	C <sub>2</sub> H <sub>6</sub>	30.07	-47.5	-48.0	1.5	-1.0
Propylene	C <sub>3</sub> H <sub>6</sub>	42.081	-45.8	-45.9	0.4	-0.3
Propane	C <sub>3</sub> H <sub>8</sub>	44.097	-46.4	-47.1	2.3	-1.5
<i>n</i> -Butane	C <sub>4</sub> H <sub>10</sub>	58.12	-45.8	-46.6	2.7	-1.7
<i>n</i> -Pentane	C <sub>5</sub> H <sub>12</sub>	72.15	-45.4	-46.3	2.9	-1.9
Benzene	C <sub>6</sub> H <sub>6</sub>	78.114	-40.6	-40.8	0.5	-0.4
<i>n</i> -Hexane	C <sub>6</sub> H <sub>14</sub>	86.18	-45.1	-46.1	3.1	-2.0
<i>n</i> -Heptane	C <sub>7</sub> H <sub>16</sub>	100.21	-45.0	-45.9	3.2	-2.1
<i>n</i> -Octane	C <sub>8</sub> H <sub>18</sub>	114.232	-44.8	-45.8	3.3	-2.2
Isooctane	C <sub>8</sub> H <sub>18</sub>	114.232	-44.7	-45.8	3.7	-2.4
<i>n</i> -Nonane	C <sub>9</sub> H <sub>20</sub>	128.26	-44.7	-45.7	3.4	-2.2
<i>n</i> -Decane	C <sub>10</sub> H <sub>22</sub>	142.29	-44.6	-45.7	3.5	-2.3
Carbon monoxide	CO	28.01	-10.1	-9.2	-3.1	+10.1
Methanol	CH <sub>3</sub> OH	32.042	-21.1	-21.5	1.4	-1.9
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	46.069	-27.8	-28.4	2.1	-2.2
Ethylene glycol	(CH <sub>2</sub> OH) <sub>2</sub>	62.07	-17.1	-18.6	5.1	-8.1
Sulfur	S	32.064	-9.2	-9.3	0.3	-0.9
Sulfur monoxide	SO	48.063	-6.3	-5.8	-1.6	+8.5

Source: Data from R. C. Weast, editor, *CRC Handbook of Chemistry and Physics*, 66th ed., CRC Press, Boca Raton, Fla., 1985.

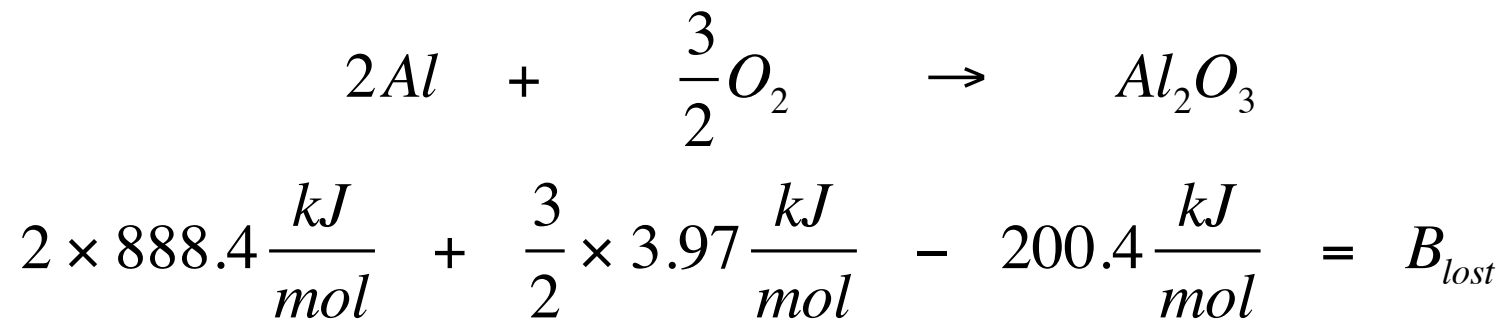
<sup>a</sup>Each constituent before and after combustion is assumed to be in its ideal-gas state at  $T_0$  and  $p_0$ .

Note that  $\Delta g^\circ \approx \Delta h^\circ$   
(lower heating value) for fuels

Ref  
Gyftopolous  
& Beretta



# Example: Oxidation of Aluminum

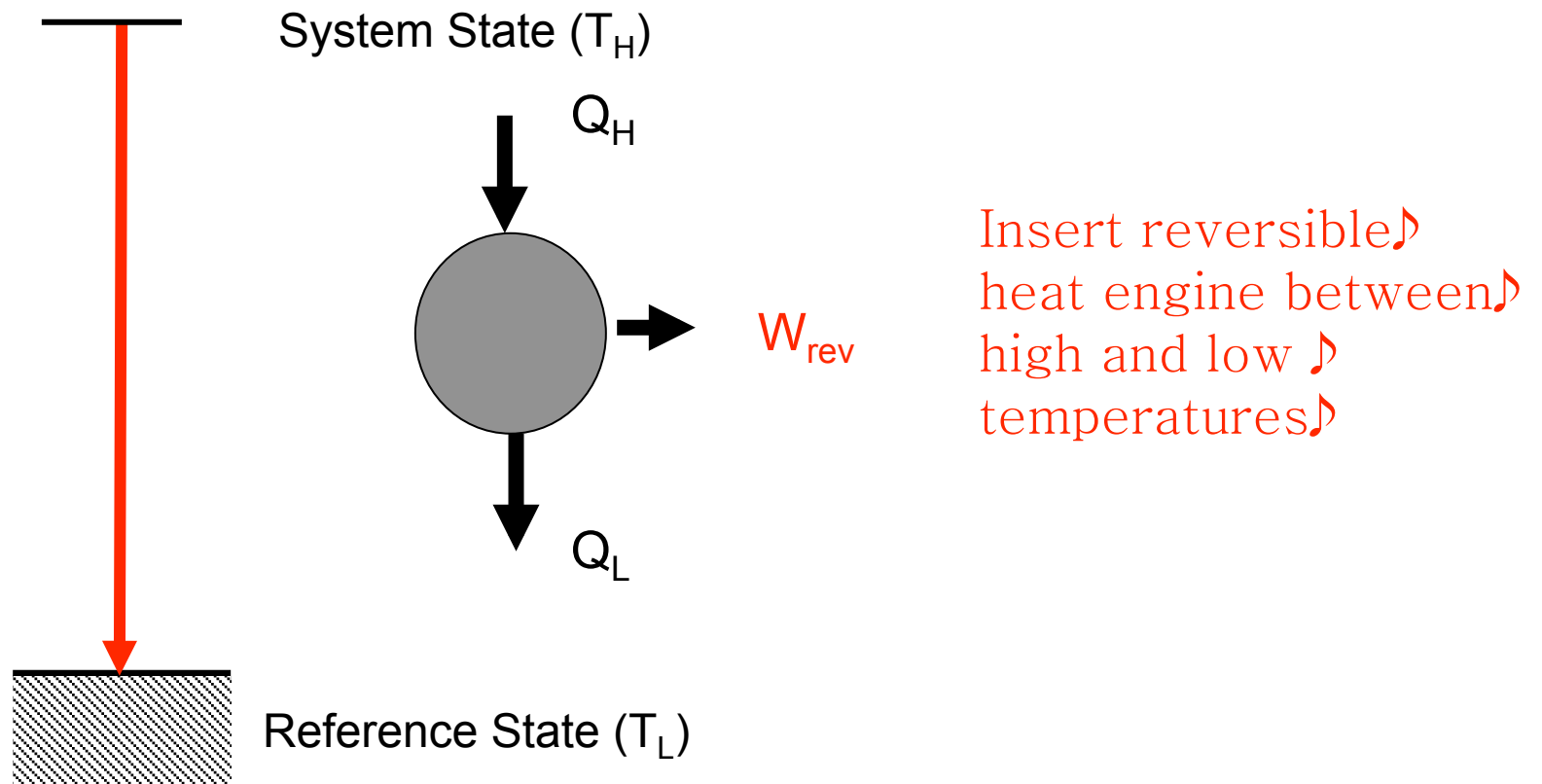


$$B_{lost} = (1776.8 + 6.0 - 200.4) = 1582.4 \frac{kJ}{mol(Al_2O_3)}$$

See Appendix of Szargut for exergy values<sub>49</sub>



# Materials can do work? 🎵



# Chemical Properties referenced to the “environment”

**Crust**

**Oceans**

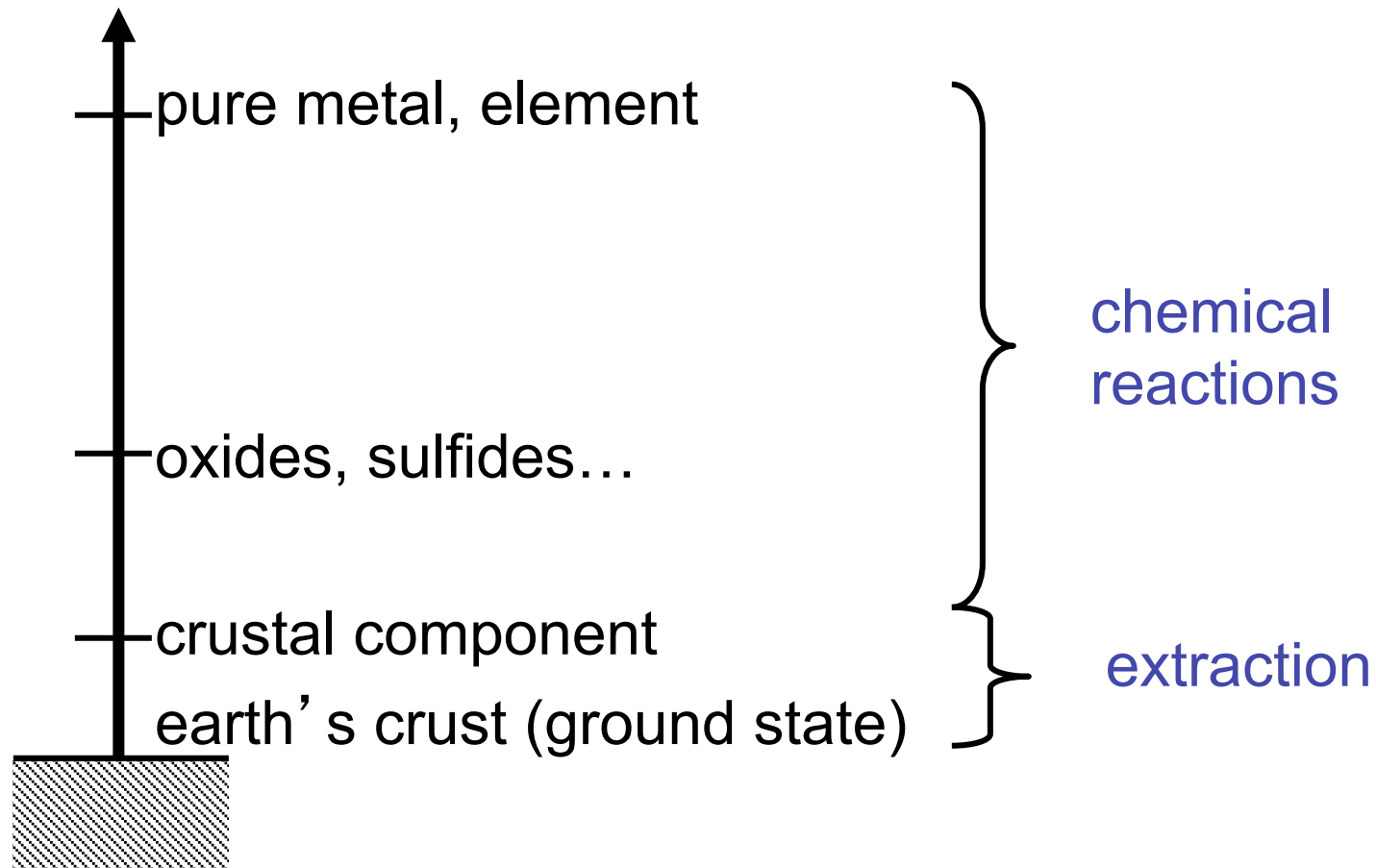
**Atmosphere**

Component of Air	Symbol	Content – %Volume
Nitrogen	N <sub>2</sub>	78.084 percent
Oxygen	O <sub>2</sub>	20.947 percent
Argon	Ar	0.934 percent
Carbon dioxide	CO <sub>2</sub>	0.033 percent
Neon	Ne	18.2 parts/million
Helium	He	5.2 parts/million
Krypton	Kr	1.1 parts/million
Sulfur dioxide	SO <sub>2</sub>	1.0 parts/million
Methane	CH <sub>4</sub>	2.0 parts/million
Hydrogen	H <sub>2</sub>	0.5 parts/million
Nitrous oxide	N <sub>2</sub> O	0.5 parts/million
Xenon	Xe	0.09 parts/million
Ozone	O <sub>3</sub>	0.0 to 0.07 parts/million
Ozone – Winter	O <sub>3</sub>	0.0 to 0.02 parts/million
Nitrogen dioxide	NO <sub>2</sub>	0.02 parts/million
Iodine	I <sub>2</sub>	0.01 parts/million
Carbon monoxide	CO	0.0 to trace
Ammonia	NH <sub>3</sub>	0.0 to trace

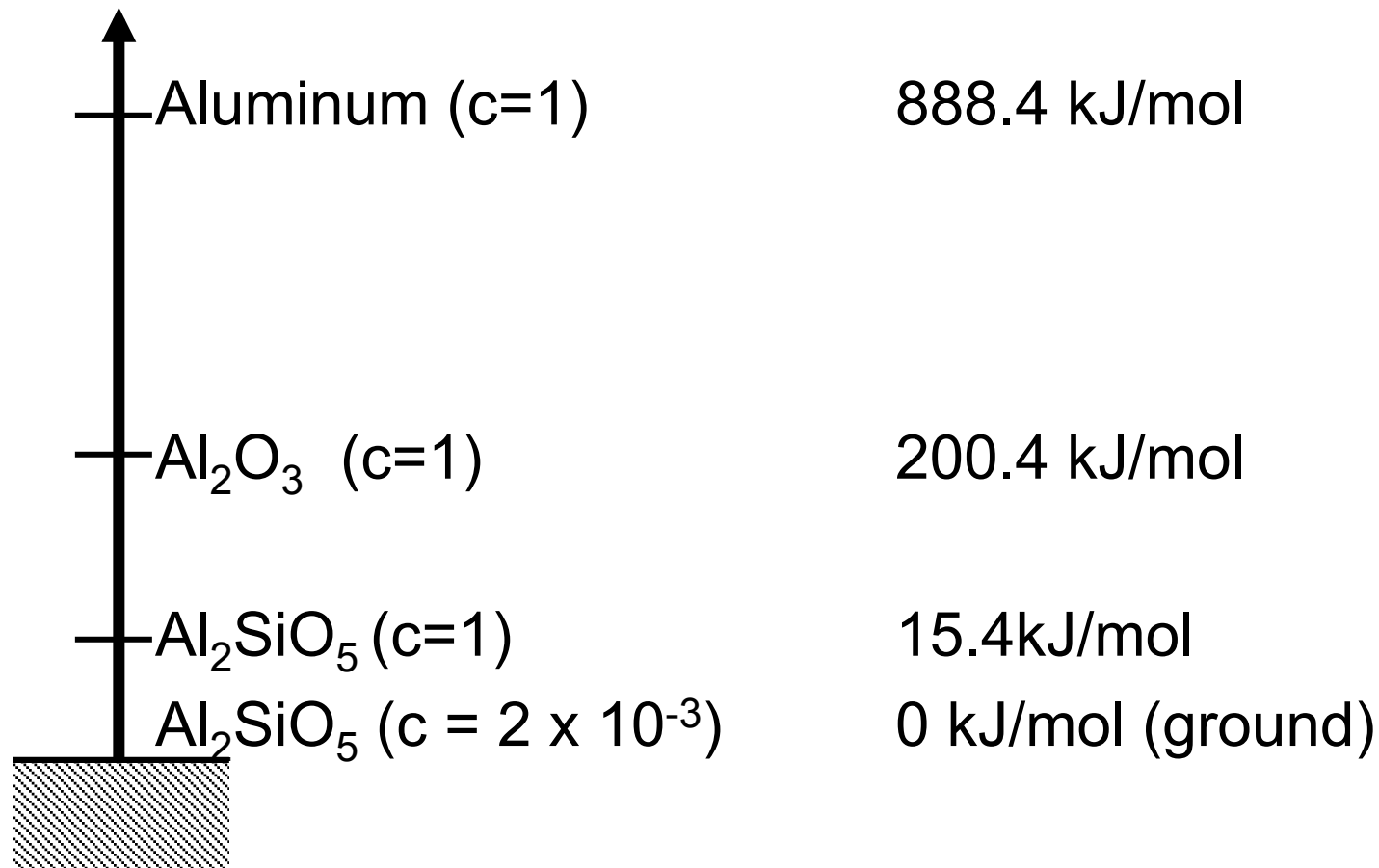
The above table is an average for clean, dry air at sea level.  
1 part/million = 0.0001 percent.

$$T_0 = 298.2 \text{ K}, P_0 = 101.3 \text{ kPA}$$

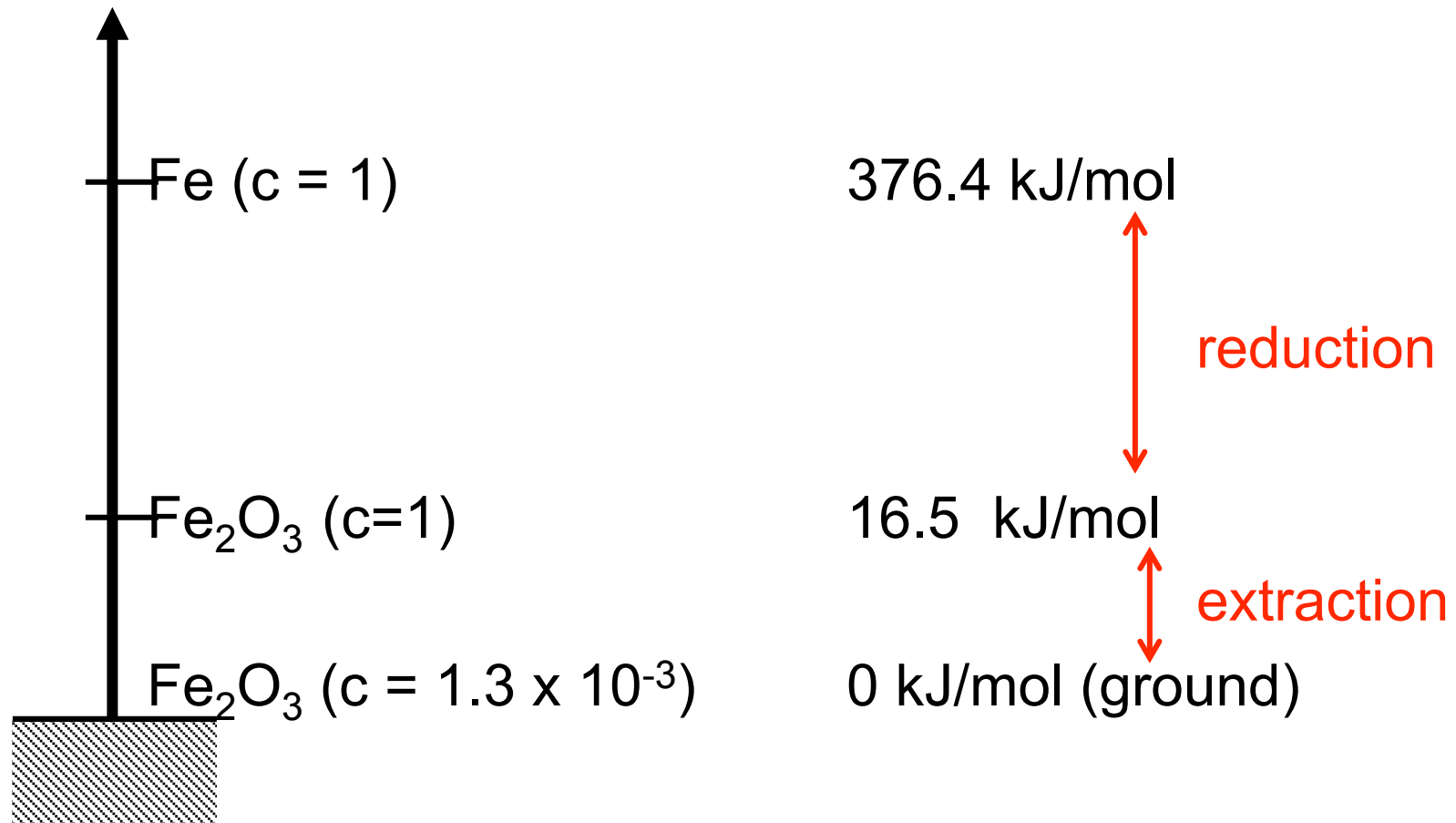
# Exergy Reference System



# Exergy Reference System



# Example; making pure iron from the crust



**Table 2.8 Solid reference species and their conventional average concentration in the external layer of the earth crust**

Chemical element	Component of the lithosphere		Reference species			Standard chemical exergy of the element, kJ/mol
	Formula	Mass fraction	Formula	Conventional standard mole fraction $x_m$	Standard chemical exergy, kJ/mol	
Al (s)	Al <sub>2</sub> O <sub>3</sub>	0.152	Al <sub>2</sub> SiO <sub>5</sub> (sillimanite)	$2 \times 10^{-3}$	15.4	888.4
Ba	BaO	$5.1 \times 10^{-3}$	—	—	—	—
Ca	CaO	$5.1 \times 10^{-2}$	—	—	—	—
Cl	Cl	$4.5 \times 10^{-4}$	—	—	—	—
Co (s)	Co	$4 \times 10^{-5}$	Co <sub>3</sub> O <sub>4</sub>	$2 \times 10^{-7}$	38.2	265.0
Cr (s)	Cr <sub>2</sub> O <sub>3</sub>	$5.2 \times 10^{-4}$	Cr <sub>2</sub> O <sub>3</sub> (s)	$4 \times 10^{-7}$	36.5	544.3
Fe (s)	FeO	$3.72 \times 10^{-2}$	Fe <sub>2</sub> O <sub>3</sub> (s)	$1.3 \times 10^{-3}$	16.5	376.4
	Fe <sub>2</sub> O <sub>3</sub>	$3.10 \times 10^{-2}$	—	—	—	—
K	K <sub>2</sub> O	$3.11 \times 10^{-2}$	—	—	—	—
Mg (s)	MgO	$3.45 \times 10^{-2}$	CaCO <sub>3</sub> · MgCO <sub>3</sub>	$2.3 \times 10^{-3}$	15.1	633.8
Mn (s)	MnO	$1.18 \times 10^{-3}$	MnO <sub>2</sub>	$2 \times 10^{-4}$	21.1	482.3
Na	Na <sub>2</sub> O	$3.71 \times 10^{-2}$	—	—	—	—
P (s)	P <sub>2</sub> O <sub>5</sub>	$2.85 \times 10^{-3}$	Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub>	$4 \times 10^{-4}$	19.4	875.8
S	SO <sub>3</sub>	$2.6 \times 10^{-4}$	—	—	—	—
Sb (s), III	Sb	$1 \times 10^{-6}$	Sb <sub>2</sub> O <sub>5</sub>	$7 \times 10^{-10}$	52.3	435.8
Si (s)	SiO <sub>2</sub>	0.591	SiO <sub>2</sub> (s)	0.472	1.9	854.6
Sn (s), white	Sn	$4 \times 10^{-5}$	SnO <sub>2</sub> (s)	$8 \times 10^{-6}$	29.1	544.8
Ti (s), II	TiO <sub>2</sub>	$1.03 \times 10^{-2}$	TiO <sub>2</sub> (s), III	$1.8 \times 10^{-4}$	21.4	906.9
U (s), III	U	$4 \times 10^{-6}$	UO <sub>3</sub> (s)	$2 \times 10^{-8}$	43.9	1190.7
V (s)	V <sub>2</sub> O <sub>5</sub>	$2.3 \times 10^{-4}$	V <sub>2</sub> O <sub>5</sub> (s)	$2 \times 10^{-6}$	32.5	712.1

# Extraction from the crust♪

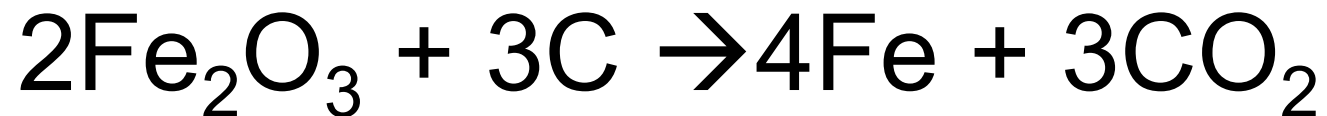
Extracting  $\text{Fe}_2\text{O}_3$  from  $c = 1.3 \times 10^{-3}$  (crust) to  $c = 1$

$$B = T_o R \ln \frac{1}{1.3 \times 10^{-3}}$$

$$B = 298.2^\circ K \times 8.314 \frac{J}{mol K} \times \ln \frac{1}{1.3 \times 10^{-3}} = 16.5 \frac{kJ}{mol}$$

Note:  $R = k N_{\text{avo}}$  (Boltzmann's constant X Avogadro's number)

## Reduction of $\text{Fe}_2\text{O}_3$ (Hematite)♪



$$2 \times 16.5 + 3 \times 410.3 - 4 \times 376.4 - 3 \times 19.9 =$$

$$B_{\text{lost}} = - 301.4 \text{ kJ}$$

this is an endothermic reaction

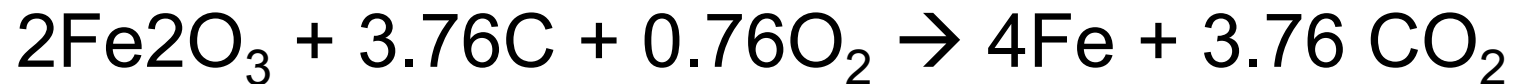
i.e. minimum energy required to reduce 2 mole of hematite



# Iron Ore Reduction

Recall  $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$  produces 394.8 kJ/mol C

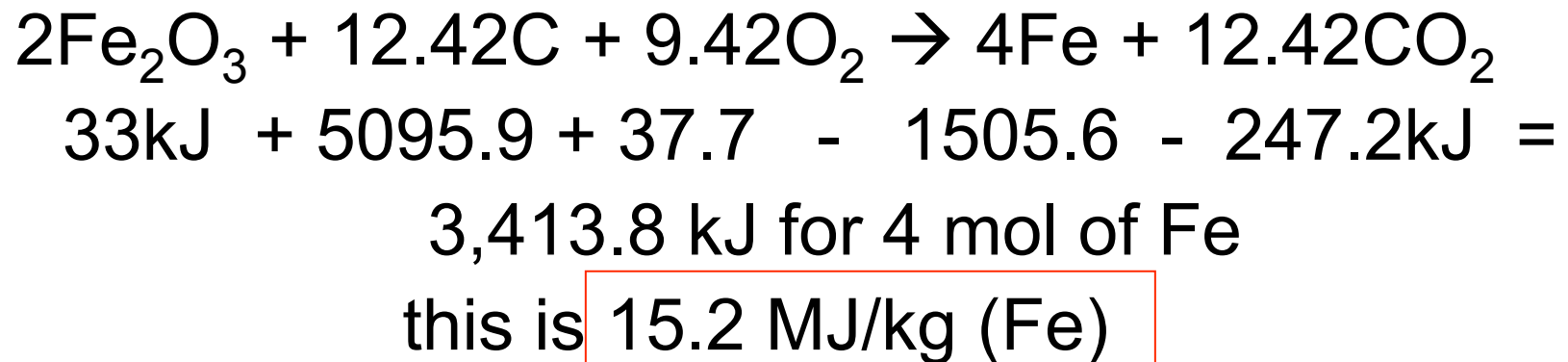
We need  $\frac{301.4}{394.8} = 0.76$  mols of carbon



# Iron Ore Reduction

but the efficiency of the use of carbon  
is only 30.3%

therefore the actual reaction is



# Iron Ore Reduction

$$\text{Fuel (C) Intensity} = \frac{12.42 \times 394.8}{4 \times 55.85 \text{ g}} = \frac{4.903 \text{ MJ}}{.2234 \text{ kg}} = 22 \frac{\text{MJ}}{\text{kg}}$$

$$\text{CO}_2 \text{ Intensity} = \frac{12.42 \times 44}{4 \times 55.85} = 2.5 \frac{\text{kg CO}_2}{\text{kg Fe}}$$

$$\text{Exergy value of pure Fe is } 376.4 \text{ kJ/mole} = 6.7 \text{ MJ/kg}$$

# Summary for Iron Ore

$$\text{fuel used} = 22 \text{ MJ/kg} \approx 15.2(B_{\text{lost}}) + 6.7(B_{\text{Fe}})$$



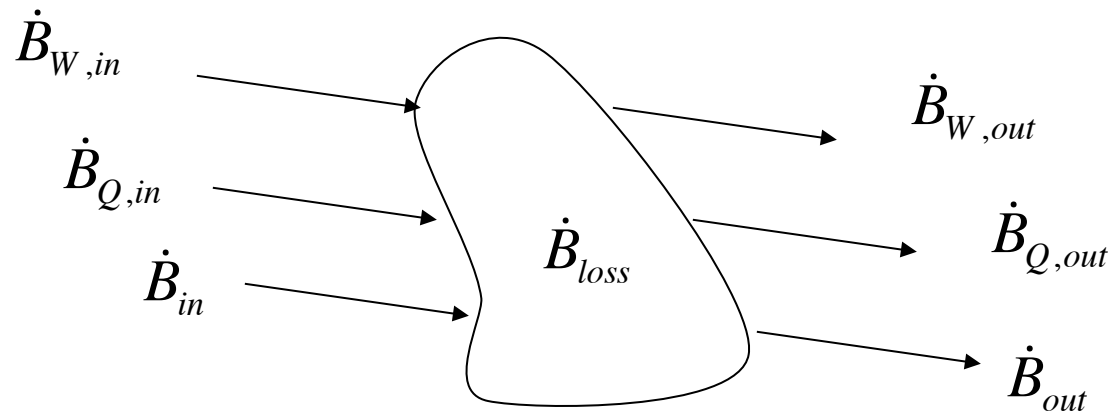
Lost exergy from making iron  
from  $\text{Fe}_2\text{O}_3$



“Credit” for producing  
pure iron from the crust

See Smil Table A.12, iron from ore 20 - 25 MJ/kg

# 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*