4EB00 Special Topic Thermodynamics and Combustion

Cycle analysis of a jet-engine

Lecture 1

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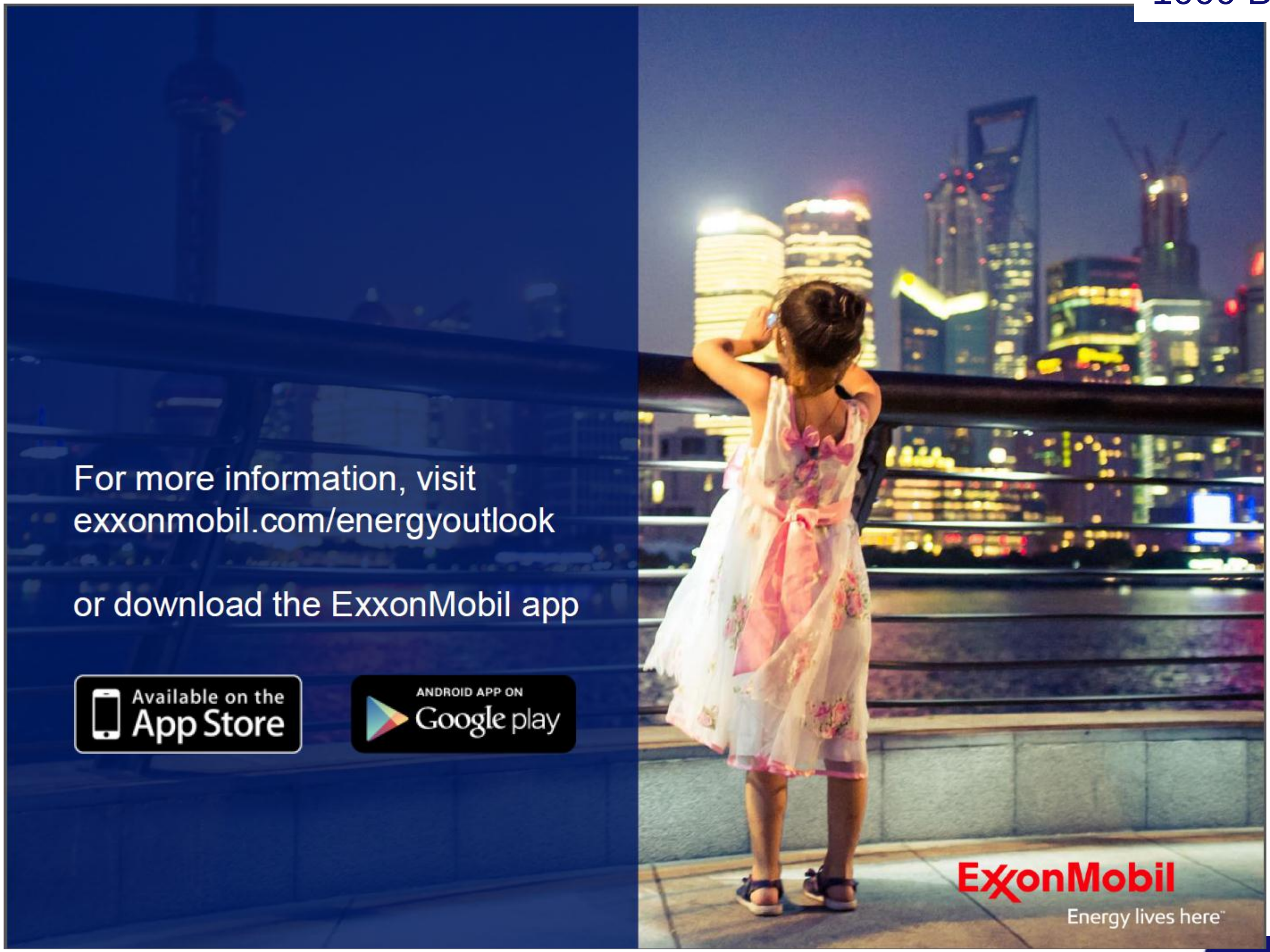
Where innovation starts

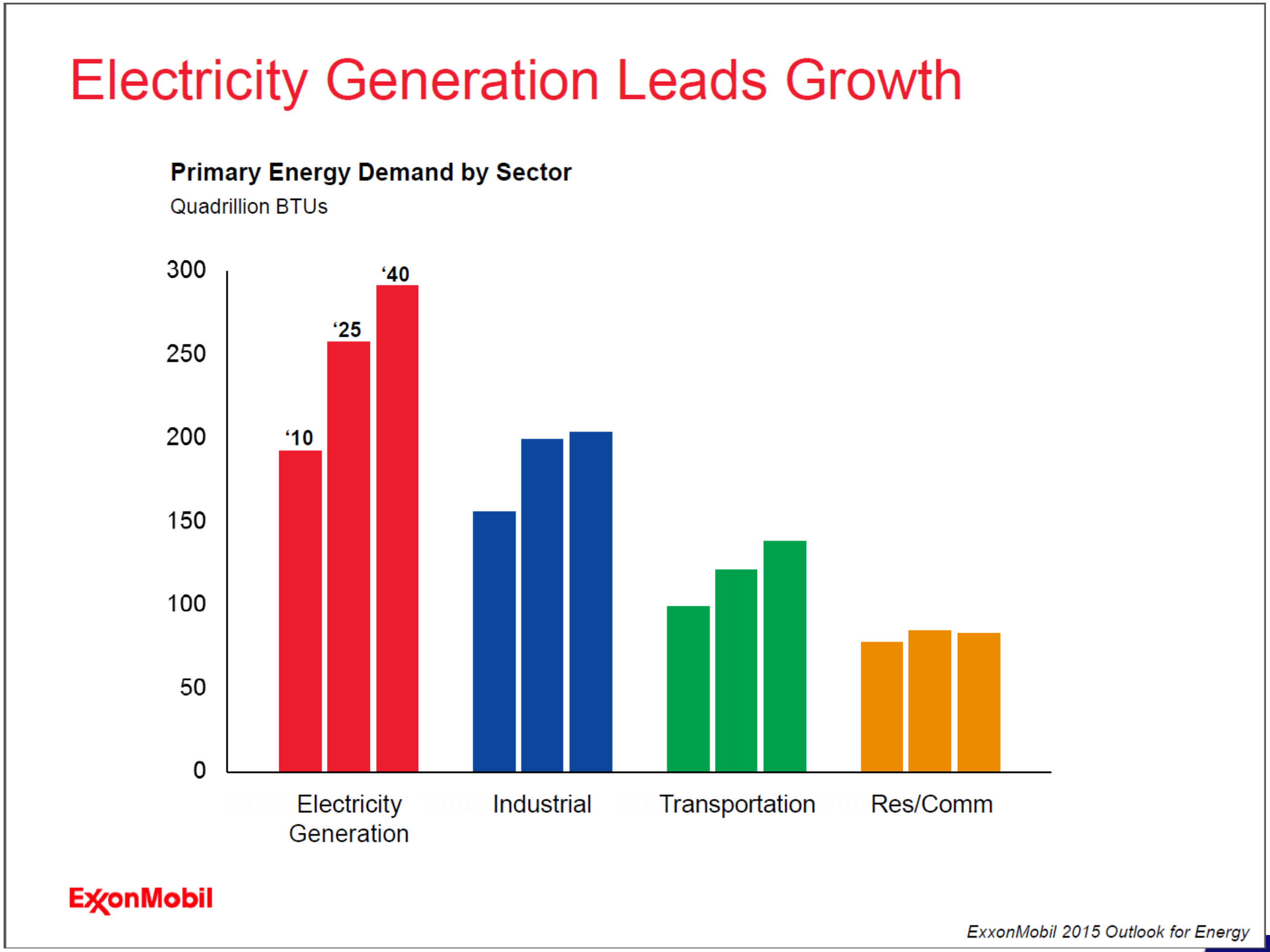
Why bother about combustion

Quadrillion=10^{15}.
10^{15} J = Peta Joule

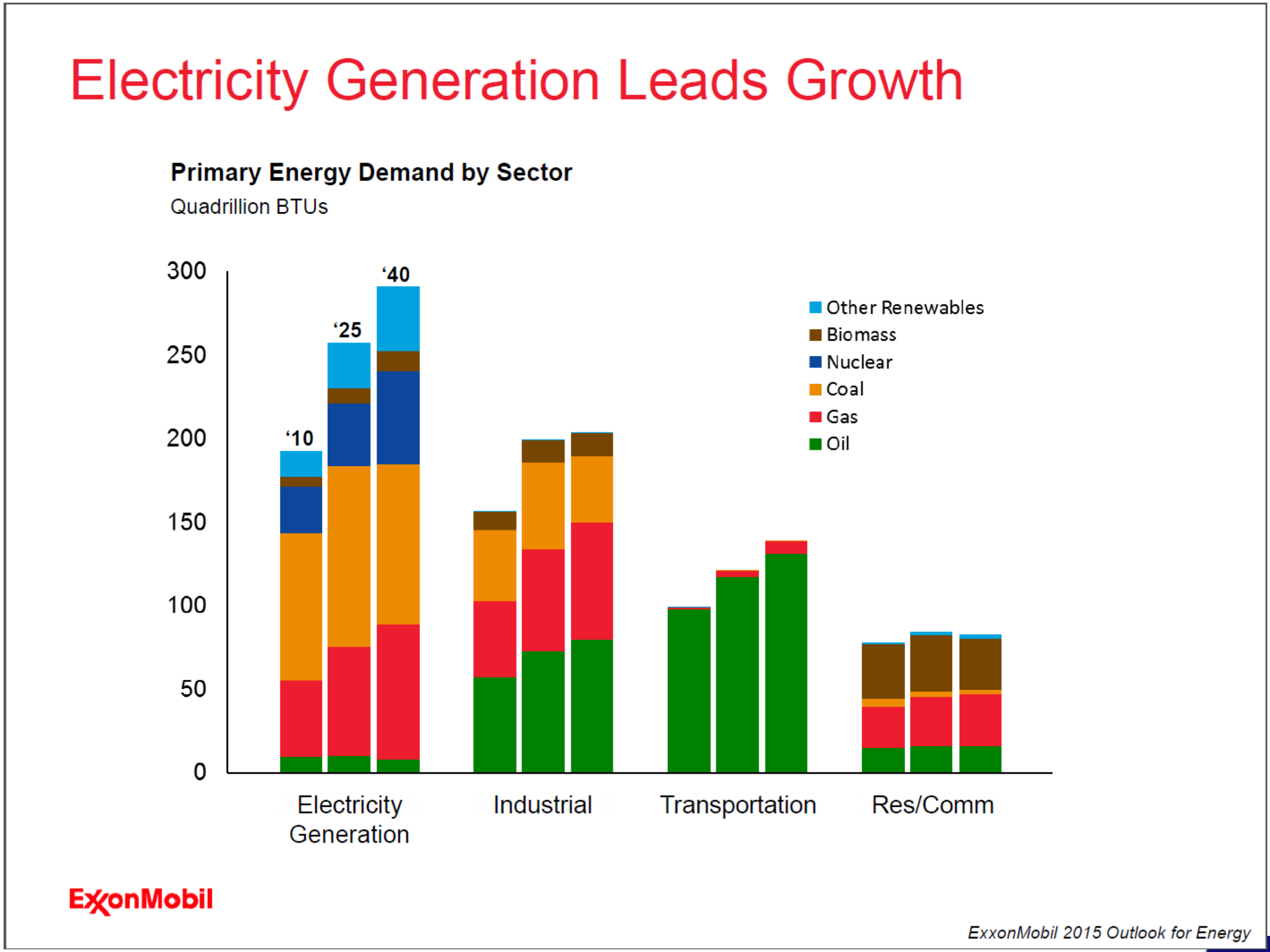
1000 BTU~1MJ



What do we need



Where does it come from



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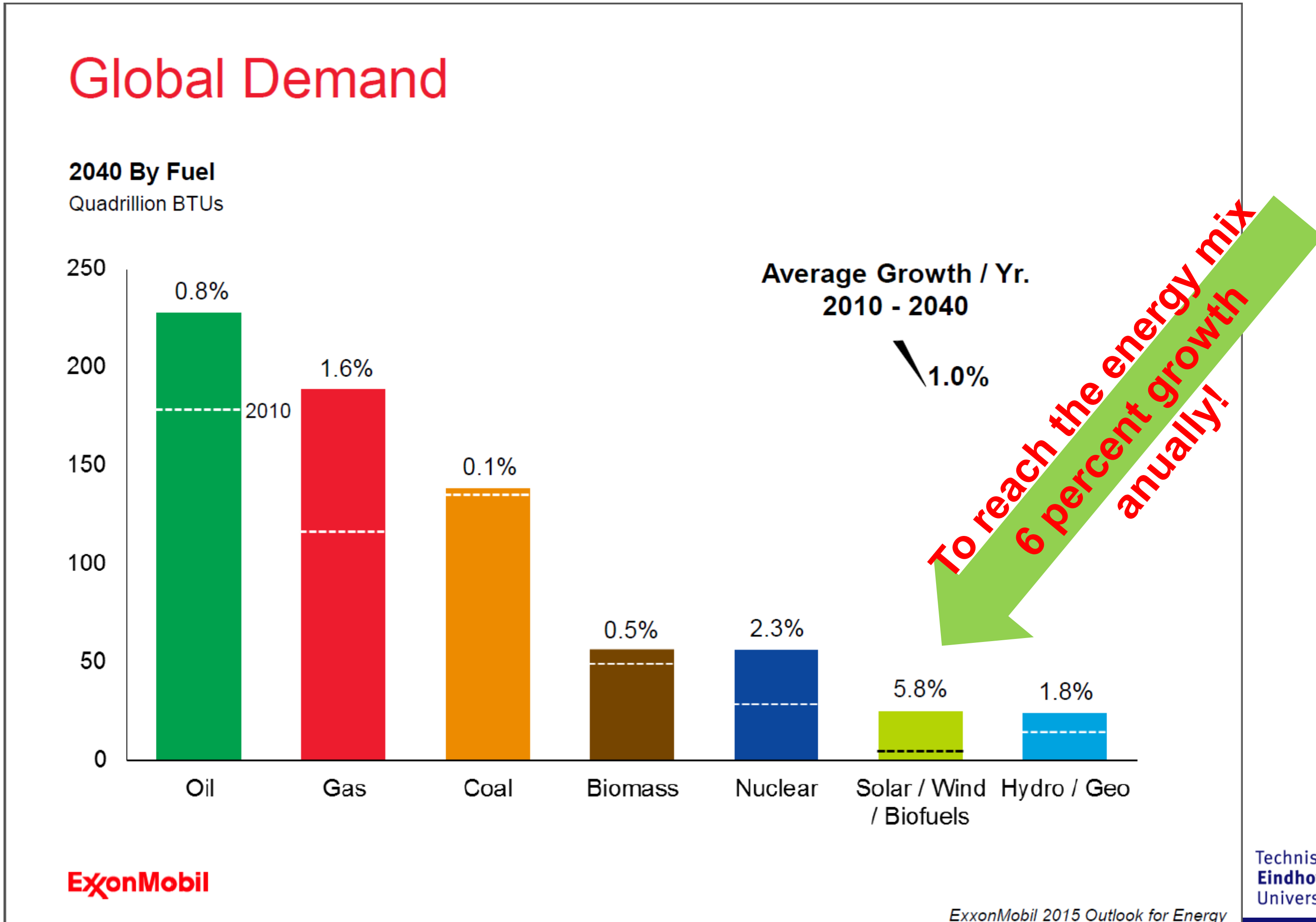
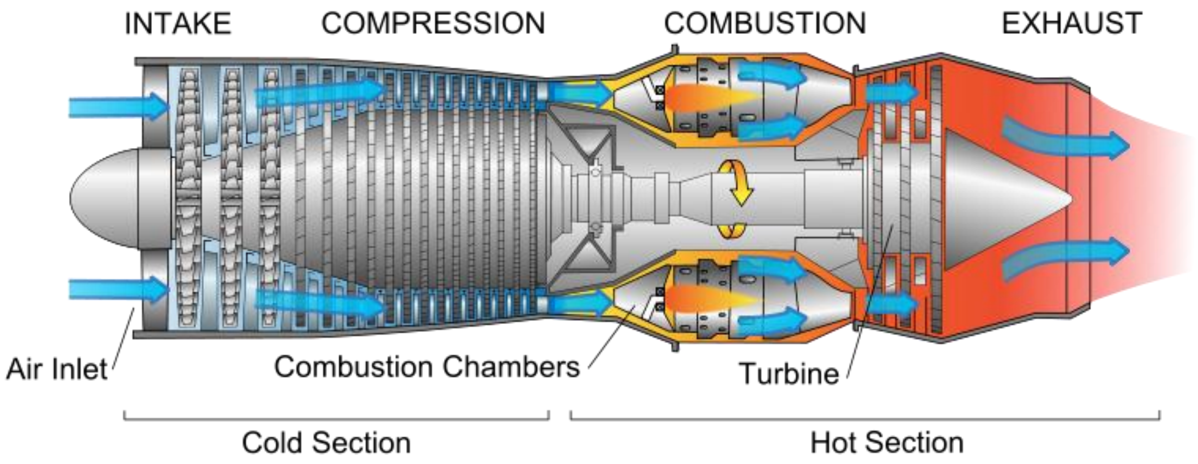
What annual growth is needed



The JetEngine

- **The combustor drives the application!**



- **How is combustion related/incorporated to/in thermodynamics**

Contents

- **Ideal Gas mixtures**
  - **Thermodynamic Properties of a mixture (2.9)**
  - **Where hides combustion**
  - **Adiabatic flame temperature, an application of Nasa thermodynamic tables.**

- **Cycle analysis of a jet engine using thermodynamic tables**
  - **Combustor**
  - **Diffusor**
  - **Etc..**

Ideal gas mixtures

- **How to define/characterize a mixture**

  - **Mole fractions**

$$X_i = \frac{N_i}{\sum_{i=1}^{J} N_i} = \frac{N_i}{N_{tot}}$$

  - **Mass fractions**

$$Y_i = \frac{M_i}{\sum_{i=1}^{J} M_i} = \frac{M_i}{M_{tot}}$$

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Ideal gas mixtures

- **Equation of state (double ideality)**
  - **Each species ideal gas (ideal solution)**

$$P_i V = N_i R_u T$$

  - **Sum it over all constituents**

$$\sum_{i=1}^{J} P_i V = \sum_{i=1}^{J} N_i R_u T$$

$$= N_{tot} R_u T = PV$$

Dalton's law

$$\sum_{i=1}^{J} P_i = P$$

Double ideality

Because mixture is also considered to be an ideal gas

Standardized properties

- **Remember eqs 2.33c calorific state**
- **For reactive mixtures it is important to use the so-called 'Standardized Enthalpy'**

$$\overline{h}_i(T) = \overline{h_{f,i}^0}(T) + \int_{T_{ref}}^{T} \overline{c_p}(T')\,dT'$$

nb $\overline{\text{overbar}}$ means units per mole here [J/mole] for $\overline{h}$ and [J/mole/K] for $\overline{c}_p$

- **Definition of $\overline{h_{f,i}^0}(T)$ is important now. It will explain why combustion creates high temperatures.**

Standardized properties: Nasa polynomials

- **Sometimes/many times it is more convenient to work in a mass based (wo overbar) framework**

$$\boxed{h_i(T) = h^0_{f,i}(T) + \int_{T_{ref}}^{T} c_p(T')\,dT' \text{ for each component } i \text{ in the mix}}$$

- **For determining conditions during re-entry of the Apollo return pod Nasa has determined these standardized properties for many components.**

Makes life easy for us. Let's use them.

Practice at home with exercises script.

Answers will be on oase for reference

Standardized properties: Nasa polynomials

At home exercise 1: **Compute h of O_2 and O.**

1. **determine** $h_{O_2}\left(T_{ref}\right)$
2. **determine** $h_{O}\left(T_{ref}\right)$**, see also book page 130**

3. **Determine enthalpy of formation** $h^0_{f,O}, h^0_{f,N}, h^0_{f,H}$
4. **Determine enthalpy of formation** $\bar{h}^0_{f,O}, \bar{h}^0_{f,N}, \bar{h}^0_{f,H}$

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Standardized properties: Nasa polynomials

Answers exercise 1:

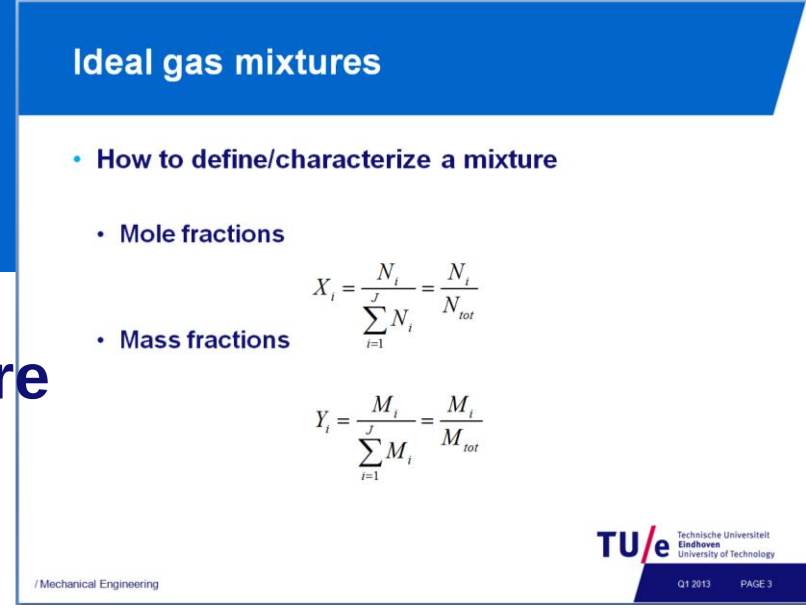
1. **determine** $h_{O_2}\left(T_{ref}\right)$=5.11e-04 [J/kg/K]
2. **determine** $h_O\left(T_{ref}\right)$=1.56e+07 [J/kg/K] **see also book page 130**
3. **Enthalpy of formation**

$$\begin{aligned} h^0_{f,O} &= 1.56\text{e+07 [J/kg/K]} \\ h^0_{f,N} &= 3.37\text{e+07 [J/kg/K]} \\ h^0_{f,H} &= 2.16\text{e+08 [J/kg/K]} \end{aligned}$$

4. **Enthalpy of formation**

$$\begin{aligned} \bar{h}^0_{f,O} &= 2.49\text{e+05 [kJ/kmol/K]} \\ \bar{h}^0_{f,N} &= 4.73\text{e+05 [kJ/kmol/K]} \\ \bar{h}^0_{f,H} &= 2.18\text{e+05 [kJ/kmol/K]} \end{aligned}$$

Ideal gas mixtures



- **Calorific relations for a mixture**
  - **Per unit mass**

$$u_{mix}(T) = \sum_i Y_i u_i(T)$$
$$c_{V,mix}(T) = \sum_i Y_i c_{V,i}(T)$$
$$etc...$$

  - **Per unit mole**

$$\bar{u}_{mix}(T) = \sum_i X_i \bar{u}_i(T)$$
$$\bar{c}_{V,mix}(T) = \sum_i X_i \bar{c}_{V,i}(T)$$
$$etc...$$

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Ideal gas mixtures

At home exercise 2: Compute properties of air.

1. **Determine composition of air(N2/O2)** X_i, Y_i
2. **Determine** $h_{air}\left(T_{ref}\right)$. And plot $h_{air}\left(T=[250-2000]\right)$
3. **Determine specific heat capacity**
   $$c_{p,air}\left(T_{ref}\right), c_{p,air}\left(T=[250-2000]\right)$$

Ideal gas mixtures

At home exercise 2: Compute properties of air.

1. **Determine composition of air(N2/O2)** X_i, Y_i
2. **Determine** $h_{air}\left(T_{ref}\right), h_{air}\left(T=[300-2000]\right)$
3. **Determine specific heat capacity** $c_{p,air}\left(T_{ref}\right), c_{p,air}\left(T=[300-2000]\right)$

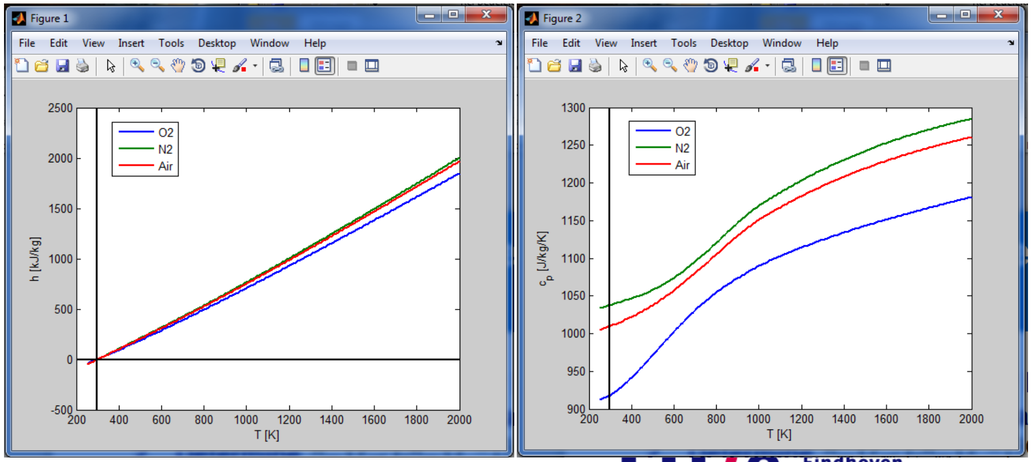
Ans1

Name	Xi	Yi
O2	0.210000	0.232918
N2	0.790000	0.767082

Ans2/3

Name	href	cpref
O2	0.00051	918.104
N2	51.04356	1037.755
Air	39.15474	1009.886

Ans2/3



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Contents

- Ideal Gas mixtures
  - Thermodynamic Properties of a mixture (2.9)
  - Where hides combustion?
  - Exercises: Constant volume explosion (ex3), Adiabatic flame temperature (ex4) (*application of Nasa thermodynamic tables*).

- Cycle analysis of a jet engine using thermodynamic tables
  - Combustor
  - Diffusor
  - Etc..

Ex3 Constant Volume Explosion

Model System

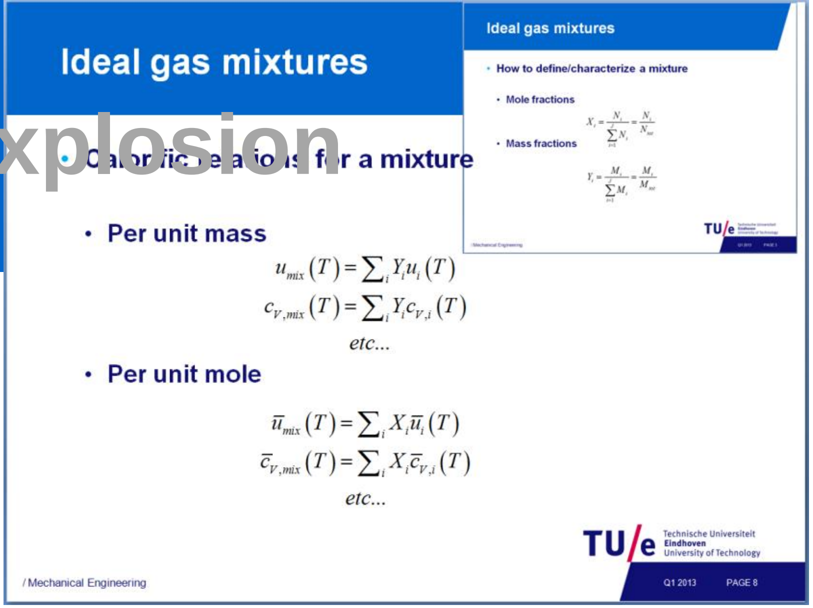
- **Adiabatic**
- **Constant volume**
- **Closed**
- **Constant mass**

$$E_2 - E_1 = \cancel{Q} - \cancel{W} + \cancel{\sum_{boundaries} m_b h_b}$$

$$E_2 - E_1 = 0$$

$$\boxed{u_{mix,2} - u_{mix,1} = 0}$$

Ex3 Constant Volume Explosion



- **Apparently**

$$\boxed{u_{mix,2} - u_{mix,1} = 0}$$

- **Given initial state**
  - **0.15 moles of acetylene (C_2H_2) and 2 moles of air. Volume of vessel is 50 liter. Due to fire T=800K. Fire is out. Mixture is going to ignite.**

Ex3 Constant Volume Explosion

Exercise 3, Constant Volume combustion of 0.15 moles of acetylene (C_2H_2) and 2 moles of air. Volume of vessel is 50 liter. T=800K.

Initial State

given molar fraction of O_2 in air is 0.21 and N_2 in air 1-0.21=0.79.

- **Determine $X_{i,1}$ of initial mixture**
- **Determine $Y_{i,1}$ of initial mixture**
- **Determine $u_{mix,1}$ using the polynomials!**

Final State

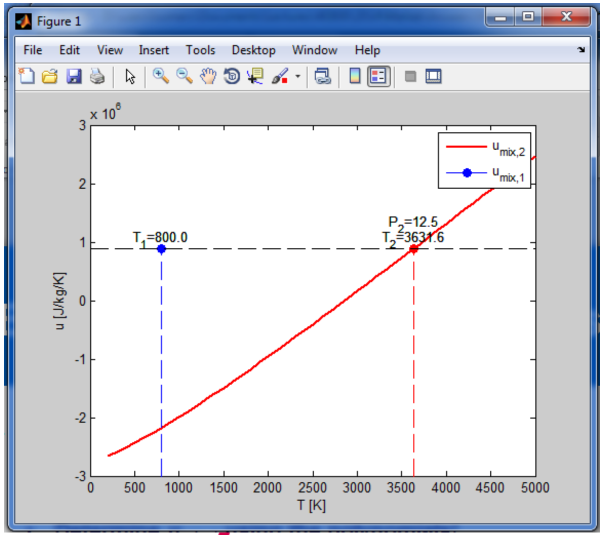
- **Determine $X_{i,2}$ of final mixture (after combustion!)**
- **Determine $Y_{i,2}$ of final mixture**
- **Determine $u_{mix,2}$ *(T) for a range of T and plot it. Compare to* $u_{mix,1}$**
- **Determine T_2 and p_2.**

Ex3 Constant Volume Explosion

- **Exercise 3**
  - **Determine X_i of mix**
  - **Determine Y_i of mix**
  - **Determine $u_{mix,1}$ using the polynomials!**
  - **Determine $X_{i,2}$ of mix (nb after combustion)**
  - **Determine $Y_{i,2}$ of mix**
  - **Determine $u_{mix,2}$ *(T) for a range of T. Compare to* $u_{mix,1}$**
  - **Determine T_2 and p_2.**

	X_i	Y_i	X_i	Y_i
	Initial		Final	
C2H2	0.069767	0.063398	0.000000	0.000000
O2	0.195349	0.218151	0.021687	0.023373
N2	0.734884	0.718451	0.761446	0.718451
CO2	0.000000	0.000000	0.144578	0.214312
H2O	0.000000	0.000000	0.072289	0.043864

	Initial	Final
T [K]	800.00	3631.62
P [bar]	2.860178	12.530943



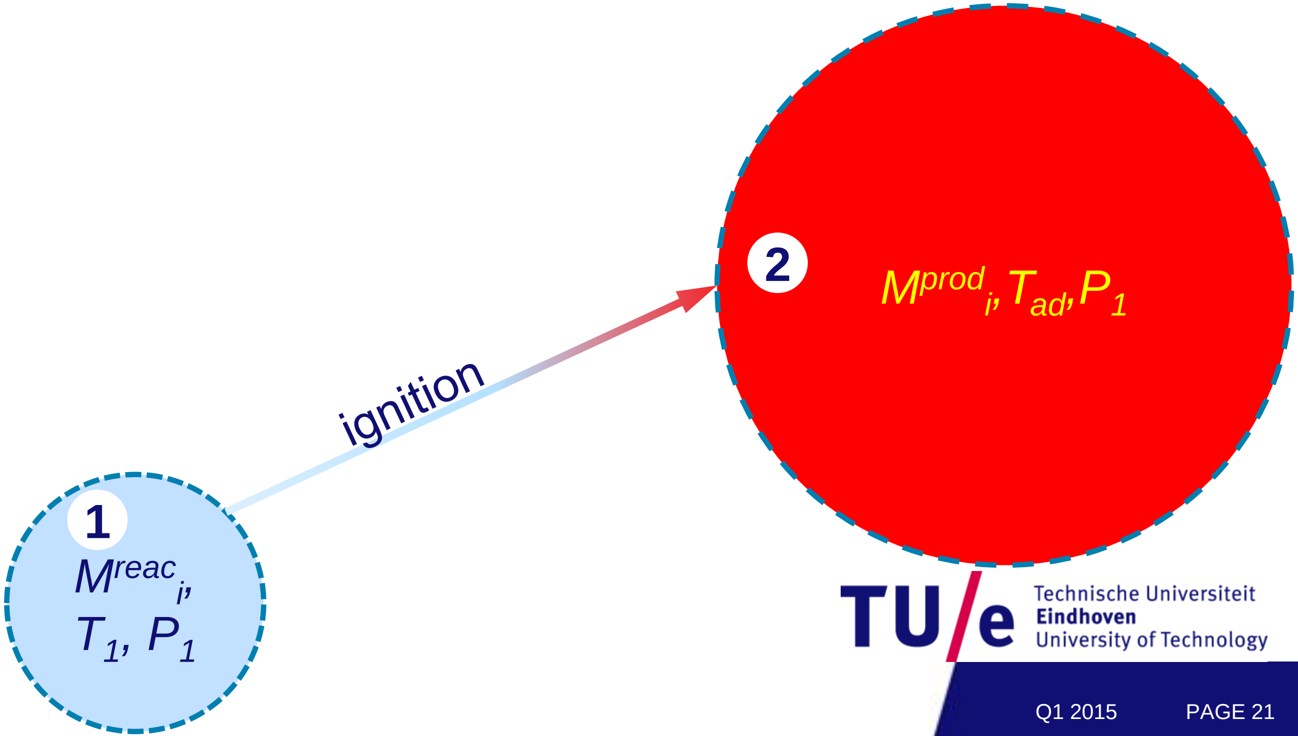
Ex3 Constant Pressure Explosion

Exercise 4

- For the fuels CH_4,C_2H_6,C_3H_8 and CO determine the adiabatic flame temperature for stoichiometric conditions.

  nb now $h_{mix,1} = h_{mix,2}$!!

  Due to definition of adiabatic flame Temperature



Ex4 Constant Pressure Explosion

Exercise 4

- **For the fuels CH_4,C_2H_6,C_3H_8 and CO determine the adiabatic flame temperature for stoichiometric conditions.**

  nb now $h_{mix,1} = h_{mix,2}$!!

  Due to definition of adiabatic flame Temperature

	Initial Xi	Initial Yi	Final Xi	Final Yi
CH4	0.095023	0.055167	0.000000	0.000000
O2	0.190045	0.220068	0.000000	0.000000
CO2	0.000000	0.000000	0.095023	0.151337
H2O	0.000000	0.000000	0.190045	0.123898
N2	0.714932	0.724765	0.714932	0.724765
T	298.15	[K]	2324.97	[K]
h	-256.49	[kJ/kg]	-256.56	[kJ/kg]

	Initial Xi	Initial Yi	Final Xi	Final Yi
C2H6	0.056604	0.058856	0.000000	0.000000
O2	0.198113	0.219209	0.000000	0.000000
CO2	0.000000	0.000000	0.110092	0.172281
H2O	0.000000	0.000000	0.165138	0.105784
N2	0.745283	0.721935	0.724771	0.721935
T	298.15	[K]	2379.20	[K]
h	-164.08	[kJ/kg]	-164.14	[kJ/kg]

	Initial Xi	Initial Yi	Final Xi	Final Yi
C3H8	0.040307	0.060324	0.000000	0.000000
O2	0.201536	0.218867	0.000000	0.000000
CO2	0.000000	0.000000	0.116236	0.180613
H2O	0.000000	0.000000	0.154982	0.098578
N2	0.758157	0.720809	0.728782	0.720809
T	298.15	[K]	2391.46	[K]
h	-142.03	[kJ/kg]	-142.06	[kJ/kg]

	Initial Xi	Initial Yi	Final Xi	Final Yi
CO	0.295775	0.289659	0.000000	0.000000
O2	0.147887	0.165451	0.000000	0.000000
CO2	0.000000	0.000000	0.347107	0.455110
N2	0.556338	0.544890	0.652893	0.544890
T	298.15	[K]	2663.09	[K]
h	-1142.96	[kJ/kg]	-1143.00	[kJ/kg]

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Where hides combustion

$$u_i(T) = u^0_{f,i}(T) + \int_{T_{ref}}^{T} c_V(T')\,dT'$$

$$E_2 - E_1 = \cancel{Q} - \cancel{W} + \cancel{\sum_{boundaries} m_b} h_b$$

Energy

$$E_1 = \sum_i m_{i,1} u_i(T_1)$$

$$E_2 = \sum_i m_{i,2} u_i(T_2) = E_1$$

Mainly the difference in 'enthalpy of formation' between reactants and products

$$\boxed{u_i(T) = u^0_{f,i}(T) + \int_{T_{ref}}^{T} c_V(T')\,dT'}$$

Compensated by 'sensible enthalpy'
HOT

$$E_2' = \sum_i m_{i,2} u_i(T_1)$$

Reaction Progress

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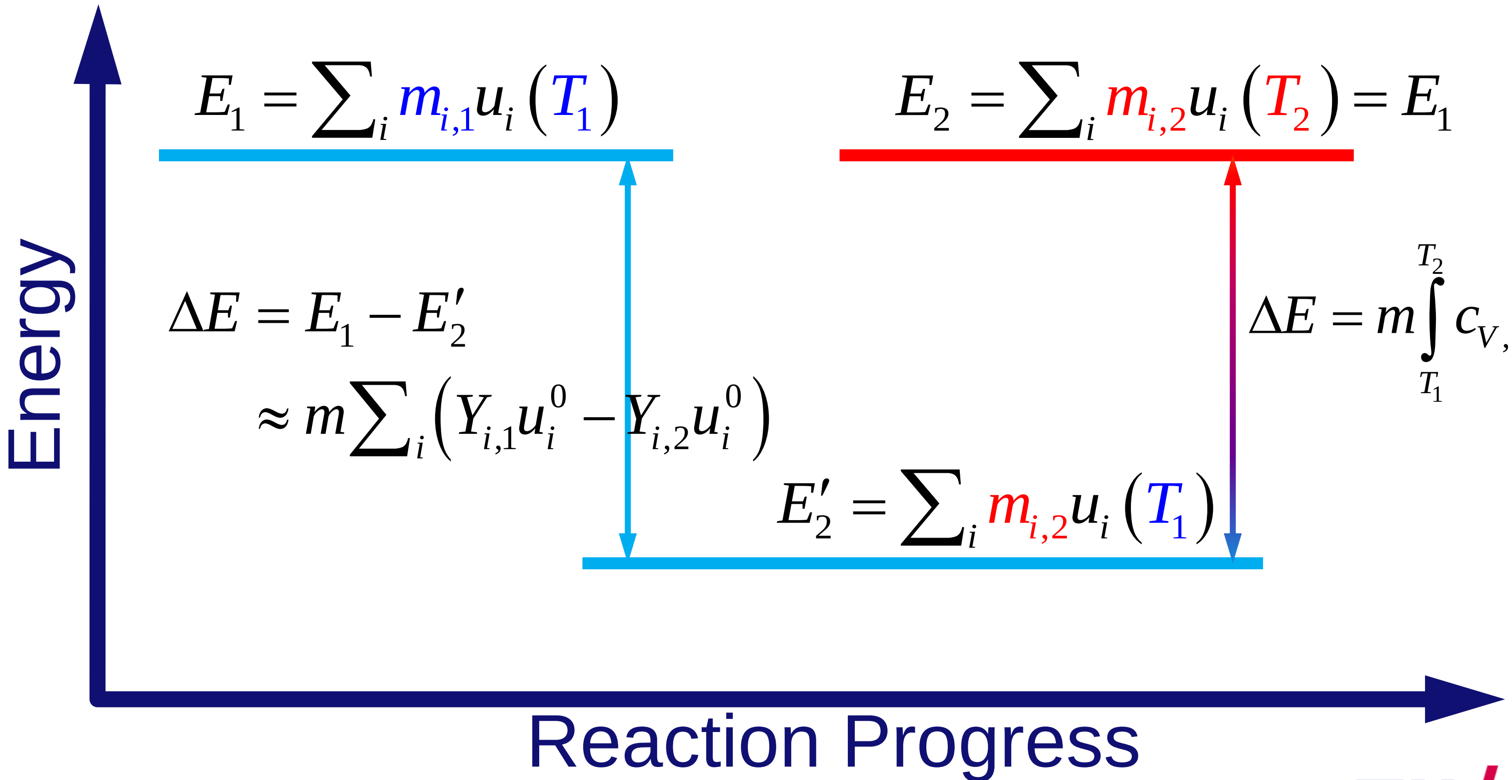
Where hides combustion

$$E_2 - E_1 = \cancel{Q} - \cancel{W} + \cancel{\sum_{boundaries} m_b} h_b$$



$$E_1 = \sum_i m_{i,1} u_i \left(T_1\right)$$

$$E_2 = \sum_i m_{i,2} u_i \left(T_2\right) = E_1$$

$$\Delta E = E_1 - E_2' \approx m \sum_i \left(Y_{i,1} u_i^0 - Y_{i,2} u_i^0\right)$$

$$\Delta E = m \int_{T_1}^{T_2} c_{V,2}\left(T'\right) dT'$$

$$E_2' = \sum_i m_{i,2} u_i \left(T_1\right)$$

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Cycle analysis of a jet engine using thermodynamic tables

Assignment 1

Compute adiabatic flame temperature of gasoline for equivalence ratios (φ) ranging from 0.2-1.

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  - **Diffusor**
  - **Compressor**
  - **Combustor etc..**

Cycle Analysis