Figure by MIT OCW.

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**SUSTAINABLE ENERGY**

**IAP 2007**

Homework #3 Due January 23, 2007
**Energy Systems Analysis**

## In class example problems

**1.** Rocky and Rochelle Jones have invented a new energy converter called **MEGA** (an abbreviation for ***M**illennial **E**nergy for **G**reen **A**pplications*) that is under consideration for acquisition by MITY Industries. The **MEGA** system supposedly directly converts natural gas to electricity by harnessing the "intrinsic" chemical energy available by reacting natural gas (essentially pure $CH_4$) with $O_2$ in air in an electrochemical fuel cell. According to the inventors, "this direct conversion avoids the inherent limitations of the 2nd Law of Thermodynamics imposed on conventional power cycle systems." Rocky and Rochelle claim that "heat to work" efficiencies of over 90% are achievable with the **MEGA**. This level of performance seems very high given that currently available, state-of-the-art integrated combined cycles that couple gas and steam turbine technologies to produce electric power at efficiencies approaching 60% with $CH_4$ feeds. Another claimed advantage of the **MEGA** system is its scalability to provide high efficiency power over a wide range of capacities (from 1 kW to 10MW) needed for distributed power application in remote regions of the world. Unfortunately, the details of how the **MEGA** operates are sketchy. We do know that air containing 20% $O_2$ enters at ambient conditions and only $CO_2$, $N_2$, and $H_2O$ vapor exit the **MEGA** again at ambient conditions. The annual average ambient air temperature on the North Slope is approximately 0°C. Selective thermodynamic data are also available (see end of problem statement).

(a) What is the maximum possible power that would be produced from a steady state flow rate of 1 mol/s of pure $CH_4$ at 1 bar, 200C available from a gas processing plant on the North Slope of Alaska? State and justify any assumptions made.

A known thermodynamics expert, Speedo Gibbs, was hired by MITY Industries to investigate, as they are skeptical that a direct $CH_4$ fuel cell has ever been operated successfully. Speedo rapidly dismantles a prototype **MEGA** device and finds two major components (1) a chemical reactor that catalytically reforms $CH_4$ into $H_2$ and (2) a conventional Pt-catalyzed electrochemical $H_2$-$O_2$ fuel cell similar to those found in the NASA space shuttle.

Speedo concludes that the overall reaction of $CH_4$ occurs by a two step process: steam reforming plus water gas shift conversion (Rx (1)), to generate $H_2$ followed by electrochemical conversion in the fuel cell (Rx (2)).

Rx (1) – $CH_4$ reforming:

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \quad \text{(steam reformer)}$$
$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \text{(water-gas shift converter)}$$
$$CH_4 + 2H_2O \Leftrightarrow CO_2 + 4H_2 \quad \text{Rx(1)}$$

Rx (2) – Electrochemical conversion of $H_2$ and $O_2$ in a fuel cell:

$$H_2 + 2OH^-_{(aq)} \Leftrightarrow 2H_2O + 2e^- \quad \text{(anode ½ cell reaction)}$$
$$\frac{1}{2}O_2 + H_2O + 2e^- \Leftrightarrow 2OH^-_{(aq)} \quad \text{(cathode ½ cell reaction)}$$
$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O \quad \text{Rx(2)}$$

Note that the sum of Rx (1) + 4×Rx (2) represents the overall reaction.

(b) Speedo's intuition tells him that the presence of the reforming step that converts $CH_4$ to $H_2$ will lower the efficiency of the **MEGA**? If this is true, the work producing potential of **MEGA** should be less. Estimate the maximum possible electric power that could be produced from the fuel cell for the same $CH_4$ feed conditions in (a). Explain your answer and state and justify all assumptions made in arriving at your revised estimate.

(c) Are there other practical process limitations that would reduce the output of the **MEGA** below its maximum value? Explain.

(d) Rocky and Rochelle Jones claim that **MEGA** operates at >90% efficiency. Is this possible? Please explain with a suitable definition and estimate of efficiency.

(e) Given your answers to parts (a)-(d) based on your analysis, how will **MEGA** compete with today's off-the-shelf combined cycle systems?

*Data:* Standard Gibbs Energies, Enthalpies of Formation and average ideal-gas state heat capacities at 298K and 1 bar.

| Compound | $\Delta G_f^o$ kJ/mol | $\Delta H_f^o$ kJ/mol | $\Delta S_f^o$ J/mol K | $< C_P^o >$ J/mol K |
|---|---|---|---|---|
| $CO_{2(g)}$ | -394.6 | -393.8 | 2.68 | 36.8 |
| $CO_{(g)}$ | -137.4 | -110.6 | 89.93 | 29.3 |
| $CH_{4(g)}$ | -50.9 | -74.9 | -80.54 | 51.8 |
| $N_{2(g)}$ | 0 | 0 | 0 | 29.3 |
| $O_{2(g)}$ | 0 | 0 | 0 | 29.3 |
| $H_2$ | 0 | 0 | 0 | 22.15 |
| $H_2O_{(g)}$ | -228.8 | -242.0 | -44.3 | 36.8 |
| $H_2O_{(l)}$ | -237.1 | -286.0 | -164.09 | 75.3 |
| $H^+_{(aq)}$ | 1517.0 | -143.6 | -5.57 | -- |
| $OH^-_{(aq)}$ | -138.7 | 1536.2 | 5.62 | -- |

**2.** Rocky and Rochelle have hired a Life Cycle Consulting Firm - RCube (remember: Reduce, Reuse, Recycle?) to analyze the **MEGA** process. You are the **MEGA** project manager for RCube. Draw a schematic using the life cycle format to describe **MEGA** – through some end use of the electricity. Indicate major waste streams of interest (costs are also important but forget them for this homework problem).

## Homework problems

### 1. Are we missing an opportunity for energy storage and reuse?

Consider how you might recover the energy that is embodied in a large, commercial jet plane as it lands at Logan Airport in Boston. A fully loaded 747 jetliner has a total weight of about 300,000 lbs and a landing speed of about 200 mph. In its normal mode, carbon-carbon composite disc brakes and reverse thrusters are used to bring the plane to a stop during landing. What if we try to recover a portion of that energy using some of the devices discussed in class and in Chapter 16 of the text?

(a) How much energy is available for recovery?

(b) On the 747 there are 8 sets of carbon-carbon brake assembles each with a mass of 125 kg. What is the maximum temperature that would be reached is all the plane's

kinetic energy is collected and stored there? The heat capacity of the carbon composite is about 1500 J/kg K.

(c) In one scheme, the thermal energy collected in the brakes would be converted to electric energy. What is the maximum electrical work that could be produced?

(d) Using a "state of the art" Rankine cycle with a working fluid especially designed to have the thermal properties needed for maximum performance what would you estimate the actual electrical work to be?

(e) Would it be possible to use a rotating mechanical flywheel to recover even more of the energy as electrical energy? If so, describe how much energy you could capture and how you would design such a device for use on the 747. Your design should provide materials selected, mass, diameter, rotational speed, etc.

(f) Are either of these ideas plausible from a technical or economic feasibility, or sustainability perspective? Explain.

Be sure to state and justify all assumptions made in your analysis.

**2. Do heat pumps make sense in North Dakota?**

a). In conventional air-to-air heat pump systems, the atmosphere is used as a source of energy in the winter during heating season and as a sink for heat rejection in the summer during air conditioning season. Geothermal ground source heat pumps use an underground reservoir as a thermal heat source and sink. These reservoirs are usually 3 to 10 meters deep, below the depth where seasonal fluctuations occur (i.e. below the frost line). At these depths the temperature is about 15 °C. A non-freezing, non-corrosive fluid, like an aqueous solution of potassium acetate, is circulated through a coil of pipe buried in the ground to transfer thermal energy to and from the ground. How would you expect a geothermal heat pump system to perform in comparison to an air-to-air heat pump system operating under the following conditions in North Dakota?

(i) Summer day when the outside temperature is 100°F (37.8 °C)
(ii) Winter day when the outside temperature is –30°F (-34.4 °C)

People in North Dakota like to keep their homes at a constant 70°F (21.1 °C) year round. Comparisons should be made on the ideal basis for a fully reversible system and should be expressed in terms of units of heat (or cooling) transferred per unit of electrical work consumed, which is called the coefficient of performance (COP). What factors will limit the performance of practical heat pumps below their ideal limit?

**3. Is the U.S. geothermal resource large enough to provide sustainable energy?**

Some argue that geothermal energy is a dilute, low-grade energy resource that is too small to make a difference.

(a) Given that the U.S. consumes about 100 quads annually, estimate the minimum mass of hot rock needed to meet annual demand assuming the rock mass is at 200 °C initially.

(b) Given that the average geothermal temperature gradient is 20 °C/km for the US, how much thermal energy is stored in rock to a depth of 10 km corresponding to depths that can be reached using conventional drilling technology?

An ambient temperature of 25 °C can be assumed. The surface area of the U.S. is $9.37 \times 10^6$ km$^2$. You can assume that the rock mass under the surface of the US is solid granite with a density of 2500 kg/m$^3$ and a heat capacity of 1000 J/kg K.

**4. How can we reduce GHG emissions for the MEGA process?**

Using the life cycle flow diagram for the **MEGA** process, identify alternatives that would reduce total GHG emissions at each of the life cycle stages of the process: the manufacturing of raw materials, the electricity production process, and the delivery of electricity to the customer (is the customer a car? Or a commercial or residential end user? Would the end user type make a difference?)

Show a diagram, list your assumptions, and write a page of text explaining your approach and conclusions.

Note -- List all assumptions and approximations made in arriving your answers. You can use the textbook as a source for conversion factors and other needed data to solve these problems. Feel free to use other sources but make sure that you list the sources in your solution.