1.818J/2.65J/3.564J/10.391J/11.371J/22.811J/ESD166J
SUSTAINABLE ENERGY

Spring 2005

PROBLEM SET #7
Nuclear and Fossil Energy

Due April 14, 2005

1. **Millennial Energy for Green Applications.** 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 approach efficiencies of only 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, 200°C 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:

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \qquad \text{(steam reformer)}$$

$$CO + H_2O \longleftrightarrow CO_2 + H_2 \qquad \text{(water-gas shift converter)}$$

$$CH_4 + 2H_2O \longleftrightarrow CO_2 + 4H_2 \qquad \text{Rx(1)}$$

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

$$H_2 + 2OH^-_{(aq)} \longleftrightarrow 2H_2O + 2e^- \qquad \text{(anode ½ cell reaction)}$$

$$\frac{1}{2}O_2 + H_2O + 2e^- \longleftrightarrow 2OH^-_{(aq)} \qquad \text{(cathode ½ cell reaction)}$$

$$H_2 + \frac{1}{2}O_2 \longleftrightarrow H_2O \qquad \text{Rx(2)}$$

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 greater than 90% efficiency. Is this possible? Please explain with a suitable definition and estimate of efficiency.

(e) Given your answers to parts (a) through (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	ΔG_f^o kJ/mol	ΔH_f^o kJ/mol	ΔS_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. If nuclear power were to be used to displace fossil fuels in the worldwide energy economy the demand for uranium would grow rapidly. Consider the case that nuclear fission would provide half of the heat currently provided worldwide by fossil fuels.

A. If this heat were to be provided by pressurized water reactors (PWRs) how many reactors of 3000 MWt power capacity would be needed?

B. What would be the worldwide annual consumption rate of natural uranium?

C. How long would currently identified uranium resources (costing less then $100/kg U3O8) be able to satisfy this demand level?

D. Breeder reactors could increase the utilization of uranium by a factor of 50. Do you think that they would likely be important in the future nuclear power economy?

E. How does the nuclear waste from a breeder reactor differ from that of a PWR? The wastes from which type of reactor would pose a lower hazard to future generations?

F. How would you determine how much money we should spend in treating nuclear wastes today in order to avert a low probability potential fatality that might occur 3000 years into the future?

Hint: Utilize data given in class or the textbook, and at the web site of the International Atomic Energy Agency (IAEA).