Fundamentals of Advanced Energy Conversion
Spring 2004
Homework Set #1

Problem 1. The purpose of this problem is to familiarize you with the units of energy and to compare some of the characteristics of various energy sources.

A 1000 MWe power plant is being planned for the rapidly expanding city of Las Vegas. Consider three possible options for the plant: nuclear, coal and solar fueled. The total system should have a capacity factor of 90%*. Answer the following questions.

1.1 If an advanced nuclear power reactor is to be used, what amount of natural uranium will be needed to fuel the plant annually? The thermal to electrical energy conversion efficiency using a water-steam Rankine cycle with sub-critical pressure is 35%. The nuclear to thermal energy conversion efficiency in the reactor is 95%, due to the emissions of neutrinos which are not captured in the core. For simplicity assume U-235 is the only fissionable material. By weight, U-235 constitutes 0.71% of natural uranium, and the rest is U-238.   The reactor fresh fuel requires a higher fraction of U-235 (typically 4.4% in today's light water cooled reactors) which is obtained by isotopic enrichment of the natural uranium. However, due to the energy intensity of the operation of the enrichment plants when the U-235 fraction gets to be small, the discarded uranium in the enrichment process (called uranium tails) has 0.25% U-235 fraction. The fission of one gram of U-235 produces 1 MW-day worth of nuclear energy.

1.2 If the plant is to be of an advanced pulverized coal fired plant with a supercritical water-steam Rankine cycle, what is the average daily amount of coal (in kg/day) consumed to power the plant? Consult the notes from the first lecture (or other sources) for the thermal efficiency of such plants. Assume the combustion of 1kg of coal provides 27,800 Btu of energy (this is an average value, the real heat of combustion varies with the type of coal). $1J = 9.48 \times 10^{-4}$ Btu $= 0.239$cal.

1.3 If an advanced solar photovoltaic plant is to be used, with the best available solar flux-to-electricity conversion efficiency of 12%, what is the total land area required to provide the needed power? You may assume that the land needed is 2 times the flat panel area. The daily total (direct and diffuse radiation) solar energy flux near the city of Las Vegas has an annual average of 500 cal /cm^2 per day. Assume that the solar plant will have to also store sufficient energy during the day to meet an equivalent demand at night.

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* The 90% capacity factor means the plant on average over a long time (like a year) will operate 90% of the time.

Problem 2 This problem illustrates the concept of specific work, the effect of fluid density on the work required for its compression and the effect of intercooling as a means to reduce the work needed for compressing gases.

2.1 Find the pressure at which intercooling should be performed to achieve the greatest reduction in the work needed by a two-stage compressor of air from atmospheric pressure and temperature to 100 atmospheres. The air can be assumed to behave as an ideal gas, with temperature independent specific heat. Assume that each stage of the compression is isentropic and that the intercooling occurs at constant pressure returning the air to its initial temperature prior to entering the second stage.
2.2 What is the work supplied per unit mass of air being compressed?
2.3 What would be the work needed per unit mass if no intercooling was applied?
2.4 Compare the work above to the work needed to compress a unit mass of liquid water from one to 100 atmospheres. You may ignore the density and temperature changes of water during the compression.
2.5 What values would you expect for the actual compressor work in parts 2.2 and 2.3 if a practical device of reasonable size would be used instead of the ideal ones?

Problem 3 This problem introduces the concept of total energy efficiency of a transportation system.

According to Farady's Law, the heat formation of a molecule, ΔH, can also be expressed as an electrochemical potential:
$U = - \Delta H / n_e F$,
where n_e is the number of electrons participating in the chemical bonding and F is the Farady constant = 96,485 Coulomb/mol.
Only a fraction of the energy of formation is available for reversible energy conversion, which is determined by the Gibbs free energy, ΔG.
To produce hydrogen from water by electrolysis, ΔH has to be invested (in this case 286 kJ/mol at 25 C) .
However, when hydrogen combines in a fuel cell with oxygen to produce water, only the reversible energy ΔG is obtained (237kJ/mol). Since two electrons participate in the bonding of a hydrogen molecule, the theoretical voltage that can be produced in a fuel cell is 1.23 volts. In reality, there are losses due to resistance to ion motions and polarization at the electrode interfaces, so that the actual voltage obtained is much less in practice, about 0.7 volts.
3.1 What is the "power-plant to wheels" efficiency of a fuel cell powered transportation system, if the hydrogen is produced by electricity with a thermal- to electrical power conversion efficiency in the plant is 0.5?
3.2 What should the internal combustion engine (ICE) efficiency of the cars to allow the conventional transportation power system to have the same energy utilization efficiency as the electrolysis/fuel cell system? You may assume that the energy efficiency of gasoline and diesel manufacturing plants (i.e. refinery) is 96%.
3.2 If the hydrogen is obtained by methane steam reformation, which currently has 0.7 energy efficiency, what would the answers to questions 3.1 and 3.2 be?