# 16.50 Propulsion Systems
## HWK no. 5

---

This problem is an exploration of Thermochemistry for rocket nozzles, using as a tool the CEA code from NASA, which is available online at http://cearun.grc.nasa.gov.

The specific case to be studied is a rocket using Kerosene ($C\,H_{1.975}$) and Liquid Oxygen (LOX) as propellants, with the Oxidizer/Fuel mass ratio ranging from 2 to 2.8. The chamber pressure will be 70 atm., and the exit pressure will be 0.4 atm. The calculation will be done for both limiting assumptions (a) Shifting Equilibrium expansion, and (b) Frozen Chemistry expansion from the throat (Option 2 in the CEA menu). The running menu is mostly self-explanatory. Use the "Rocket" option, and later the RP-1 fuel choice (this is the Kerosene) and the O2(L) choice for the oxidizer. Notice that the code gives the vacuum specific impulse and the "specific impulse" with no specification; this latter one is for the matched pressure condition. We are interested in these, but also the "take-off" condition, at pa=1 atm.

Examine carefully your output files, and answer the following questions:

(1) Is there an optimum O/F proportion for maximum take-off performance? Is it the same for the equilibrium and the frozen cases, and if not, why not? Are these optima fuel-rich or fuel-lean?

(2) Take the case for best equilibrium performance, and select (by inspection of the results) one representative value of $\gamma$, and one of the mean molecular mass, possibly the ones at the throat. With these values, and the computed chamber temperature, do a standard "ideal gas" calculation of the characteristic velocity (c*), the exit Mach number, the exit temperature, and the specific impulse (vacuum and take-off). Compare to the CEA results and comment on the degree of agreement.

(3) For this same case, verify that the CEA exit-plane results do satisfy the conditions of atom conservation and entropy conservation. For the latter, do your own calculation of the entropy (J/kg/K) from the stated gas composition and temperature. You can use the following skeleton table of the Standard Molar Entropy (1 atm) of the main molecules involved, in J/mole/K. The table is extracted from Fundamentals of Classical Thermodynamics (Van Wylen/Sonntag):

| | 1600K | 1800K | 2000K |
|---|---|---|---|
| CO | 250.702 | 254.907 | 258.710 |
| CO2 | 296.010 | 302.990 | 309.320 |
| H2 | 180.929 | 184.833 | 188.406 |
| H2O | 253.622 | 259.371 | 264.681 |

The calculated Entropy per kg should agree fairly well with that reported by CEA for the chamber.

16.50 Introduction to Propulsion Systems
Spring 2012