Homework 8 *(project 3)*

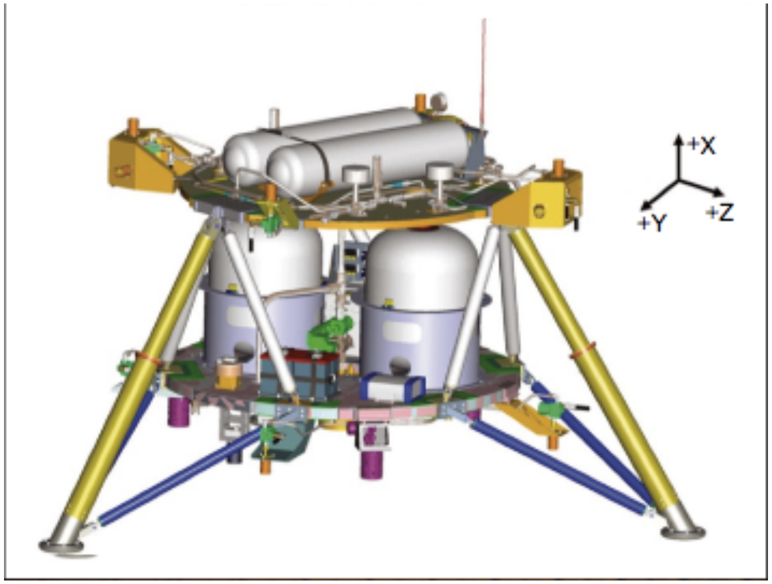
- **Assignment is due on or before the Final exam, Monday, May 2 (9:30 AM MDT)**

NASA "Mighty Eagle" Autonomous Robotic Lunar Lander Test Platform

NASA Marshall Space Flight Center and the Johns Hopkins Applied Physics Laboratory have been working together since 2005 to develop technologies and mission concepts for a new generation of small, versatile robotic landers to land on airless bodies, including the moon and asteroids, in our solar system.

As part of this larger effort, APL and the Marshall Space Flight Center worked with the Von Braun Center for Science and Innovation to construct a prototype *hydrogen-peroxide monopropellant-fueled* robotic lander that has been given the name *Mighty Eagle*.

Homework 8 *(project 3)* *(2)*



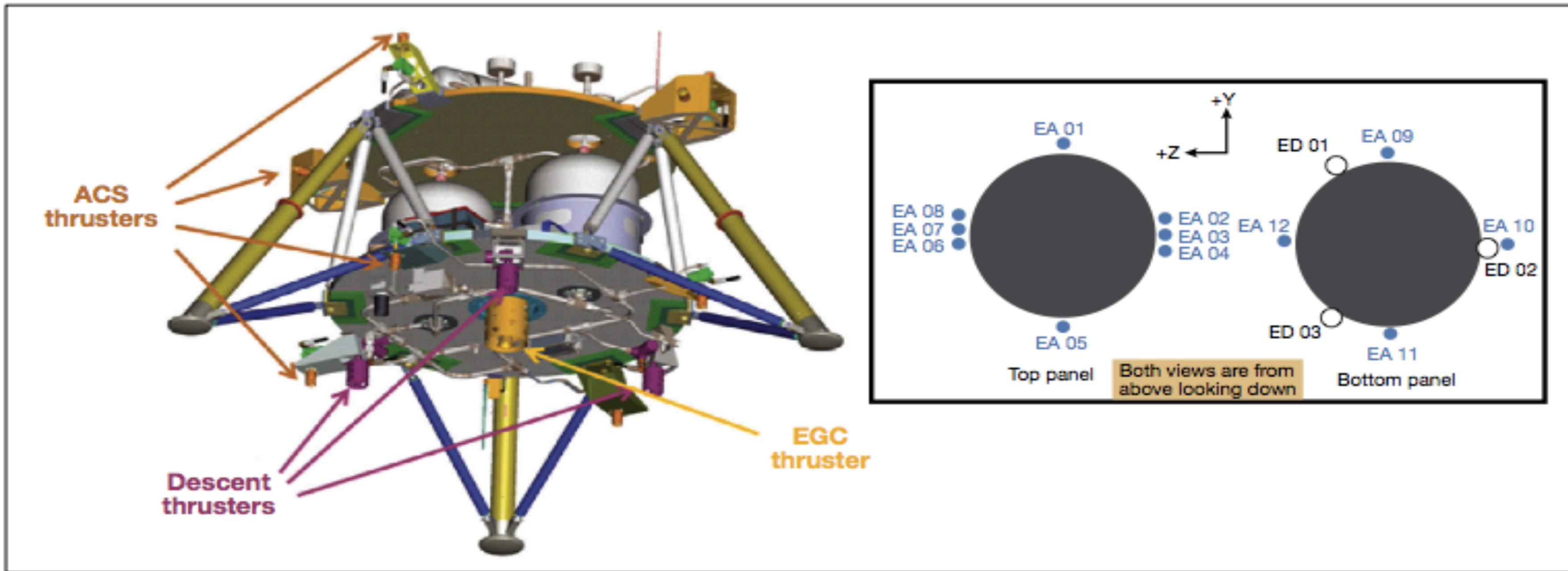
• Hydrogen peroxide was chosen for the prototype system because its decomposition by products, steam and oxygen, are both nontoxic, and it provides sufficient energy density to achieve the target flight times.

• A blowdown 90-98% pure hydrogen peroxide monopropellant propulsion system that is pressurized using regulated high-purity nitrogen provides actuation for both the attitude control system (ACS) and the descent control systems.

• A large throttleable monopropellant engine provides Earth gravity cancellation (EGC). The EGC engine nominally produces a thrust of five-sixths the weight of the lander throughout the flight to approximately simulate lunar gravity for the rest of the system by nulling the difference between Earth and lunar gravity.

• A fixed EGC engine was chosen over a gimbaled design to minimize system complexity, cost, and schedule constraints.

Homework 8 *(project 3)* *(3)*



• The propulsion system was built by Dynetics in collaboration with MSFC and APL, feeds 16 mono-propellant hydrogen-peroxide thrusters: twelve 44.5 N (10 lbf) attitude control thrusters, three 267 N (60 lbf) descent engines, and the throttleable EGC engine with a maximum thrust of approximately 3114 N (700 lbf).

• The 12 attitude thrusters are grouped into six coupled pairs to allow torque to be applied independently to each of the three rotation axes of the vehicle. The three fixed descent engines provide the vertical thrust to control the vehicle's altitude and descent rate.

EGC Thruster with Monopropellant Hydrazine

Stoichiometric Decomposition Reaction for 100% peroxide:

$$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2$$

$$\left(\Delta H_f^{\,0}\right)_{H_2O_2} = -136.31\times10^3 \tfrac{kJ}{kg-mol}$$

$$\left(\Delta H_f^{\,0}\right)_{H_2O} = -241.82\times10^3 \tfrac{kJ}{kg-mol}$$

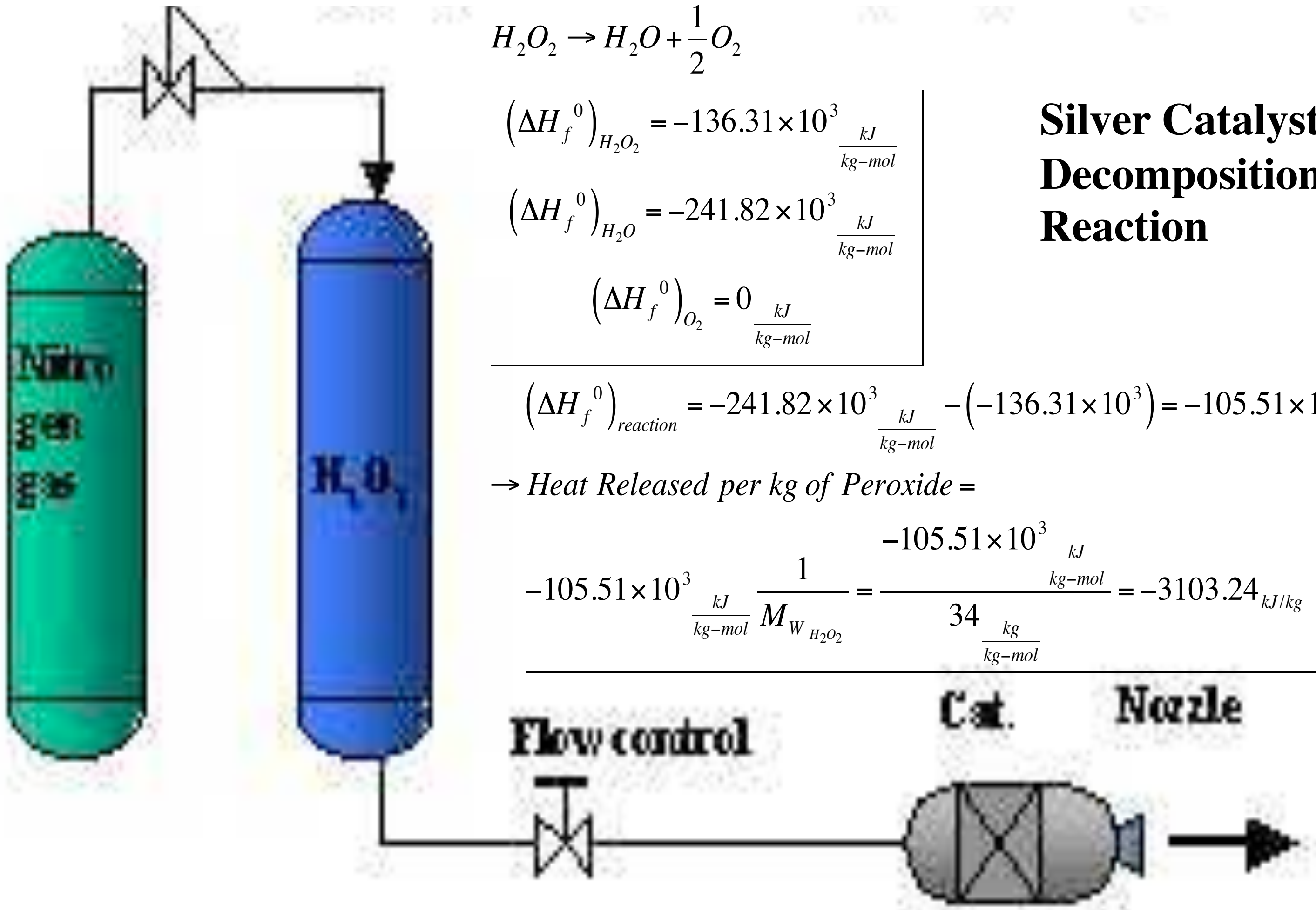
$$\left(\Delta H_f^{\,0}\right)_{O_2} = 0 \tfrac{kJ}{kg-mol}$$

Silver Catalyst Decomposition Reaction

$$\left(\Delta H_f^{\,0}\right)_{reaction} = -241.82\times10^3 \tfrac{kJ}{kg-mol} - \left(-136.31\times10^3\right) = -105.51\times10^3 \tfrac{kJ}{kg-mol}$$

$\rightarrow$ *Heat Released per kg of Peroxide* =

$$-105.51\times10^3 \tfrac{kJ}{kg-mol} \frac{1}{M_{W\,H_2O_2}} = \frac{-105.51\times10^3 \tfrac{kJ}{kg-mol}}{34 \tfrac{kg}{kg-mol}} = -3103.24_{kJ/kg}$$



Monopropellant rocket with pressurized fuel tank

(Part 1): Monopropellant Peroxide Thruster Check Case

- **Down Load the CEAGUI from the NASA Glenn Research center Web site**

http://www.grc.nasa.gov/WWW/CEAWeb/ceaRequestForm.htm

- **Assume a 4:1 Nozzle expansion ratio nozzle for the EGC engine**
- **Set up input file to run as "Rocket" Problem to calculate performance of Monopropellant Hydrazine with peroxide concentrations varying from 80% to 99%**
- **Run code in "equilibrium", with "infinite" combustor contraction ratio,**
- **H_2O_2 = "oxidizer", H_2O = "fuel"**
- **Use CEA to calculate Chamber, throat, and exit properties**
- **Iterating the code .. Find the approximate chamber pressure that gives the optimal performance for sea level operation … i.e. where does the monopropellant thruster**

Exit pressure = 1 atmosphere.

(Part 1): Monopropellant Peroxide Thruster Check Case (continued)

• For the Optimal Pressure Value, Plot the following parameters as a function of monopropellant peroxide mass concentration

i) Nozzle Exit Temperature and Stagnation Temperature
ii) Compare Nozzle Exit Temperature to Combustor temperature
Why the Difference?
iii) Nozzle Exit Mach Number
iv) C^* and C_F at Nozzle Exit
v) Vacuum (Ivac) and Optimal Isp (Isp) at Nozzle Exit.

• Based on your CEA output, at what peroxide concentration does decomposition release sufficient energy to completely vaporize all water in the peroxide solution

•Based on the Maximum thrust level of 3114 N (700 lbf), What Nozzle Throat Area is required for the optimal operating chamber pressure at 90% H_2O_2 Concentration. What is the corresponding Isp at this Thrust level.

• Calculate the Massflow corresponding to A* as a function of peroxide mass concentration

→ Assume $P_0 \cdot A^* = constant\ throughout\ the\ chamber\ and\ nozzle$

Part 1): Monopropellant Peroxide Thruster Check Case *(continued)*

- **Relationship between *% H_2O_2 concentration and CEA O/F ratio***

$$\frac{\%H_2O_2}{100} = \frac{M_{H_2O_2}}{M_{H_2O} + M_{H_2O_2}} = \frac{1}{\frac{M_{H_2O}}{M_{H_2O_2}} + 1} = \frac{1}{\frac{1}{O/F} + 1}$$

$$\frac{1}{O/F} = \frac{1}{\frac{\%H_2O_2}{100}} - 1 = \frac{1 - \frac{\%H_2O_2}{100}}{\frac{\%H_2O_2}{100}} \rightarrow \boxed{(O/F) = \frac{\frac{\%H_2O_2}{100}}{1 - \frac{\%H_2O_2}{100}}}$$

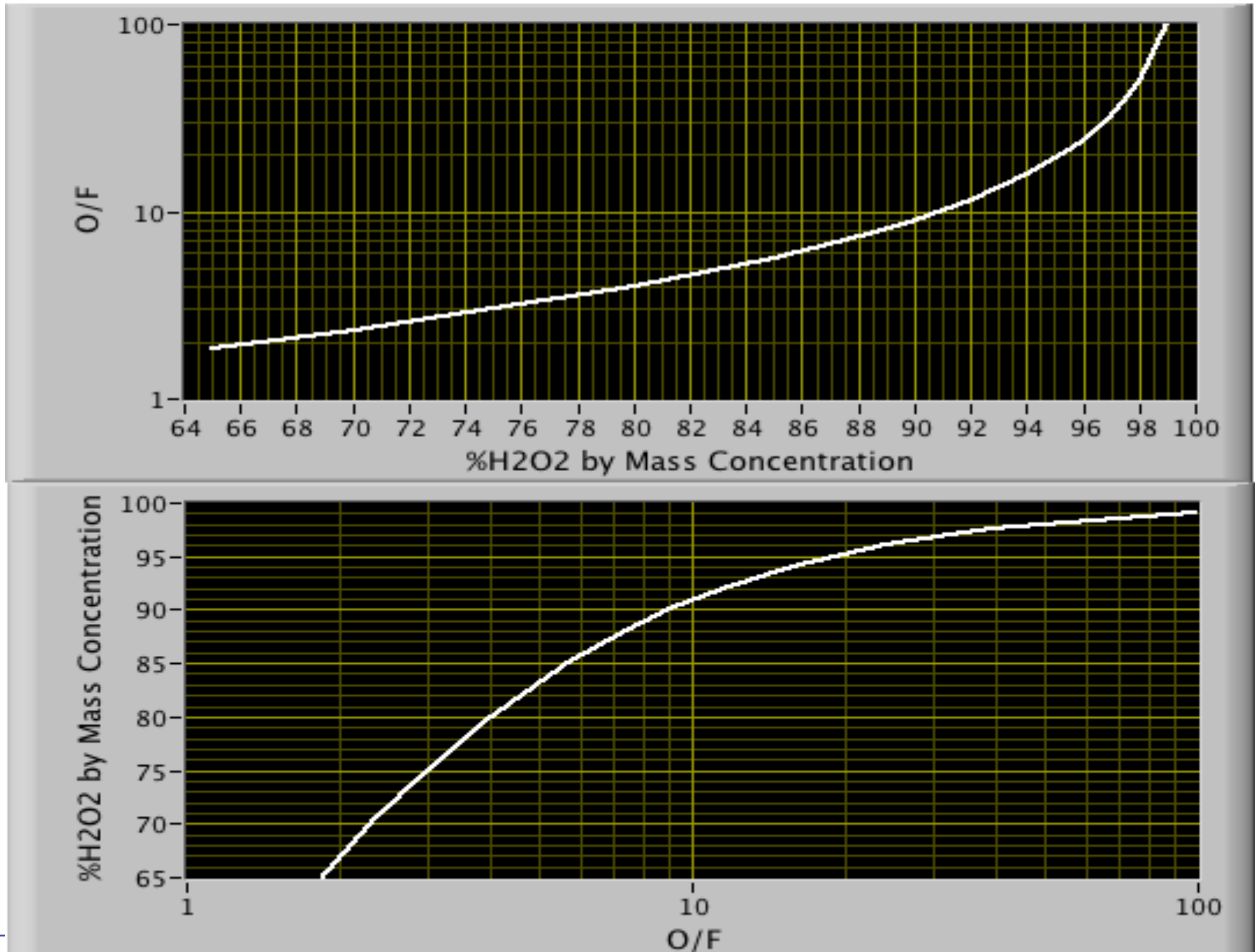
Example

$$(O/F)_{90\% H_2O_2} = \frac{0.9}{1 - 0.9} = 9:1$$

Part 1): Monopropellant Peroxide Thruster

(continued)

Equivalent O/F ratio
vs %Mass H2O2 Concentration, Monopropellant Hydrogen peroxide



Part 1): Monopropellant Peroxide Thruster

(continued)

- **Example CEA Input File … *“<filename>.inp”***

```
problem    o/
f=4,4.2636,4.5555,5,5.555,6,7,9,19.000016,24.0000,32.3333,49.0000,65.6667,99,
      rocket  equilibrium  frozen  nfz=1  tcest,k=3000
  p,bar=25,
  sup,ae/at=3.75,
react
  oxid=H2O2(L) wt=100  t,k=298
  fuel=H2O(L) wt=100  t,k=298
output
    plot p t rho h g m mw cp gam pip mach cf ivac isp
end
```

Project 3 *(Part 1)* *(continued)*

$$\rightarrow C^* = \frac{\sqrt{\gamma R_g T_0}}{\gamma\sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{(\gamma-1)}}}} = \frac{c_0}{\gamma\sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{(\gamma-1)}}}} = \frac{\sqrt{\gamma R_u}}{\gamma\sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{(\gamma-1)}}}}\sqrt{\frac{T_o}{M_W}}$$

Optimal

$$I_{sp} = \frac{Thrust}{g_o \dot{m}} = \frac{P_0 A^*}{g_o \dot{m}}\left[\gamma\sqrt{\frac{2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{(\gamma-1)}}\left[1-\left(\frac{p_{exit}}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right]}^{1/2} + \frac{A_{exit}}{A^*}\cancel{\frac{(p_{exit}-p_\infty)}{P_0}}\right]$$

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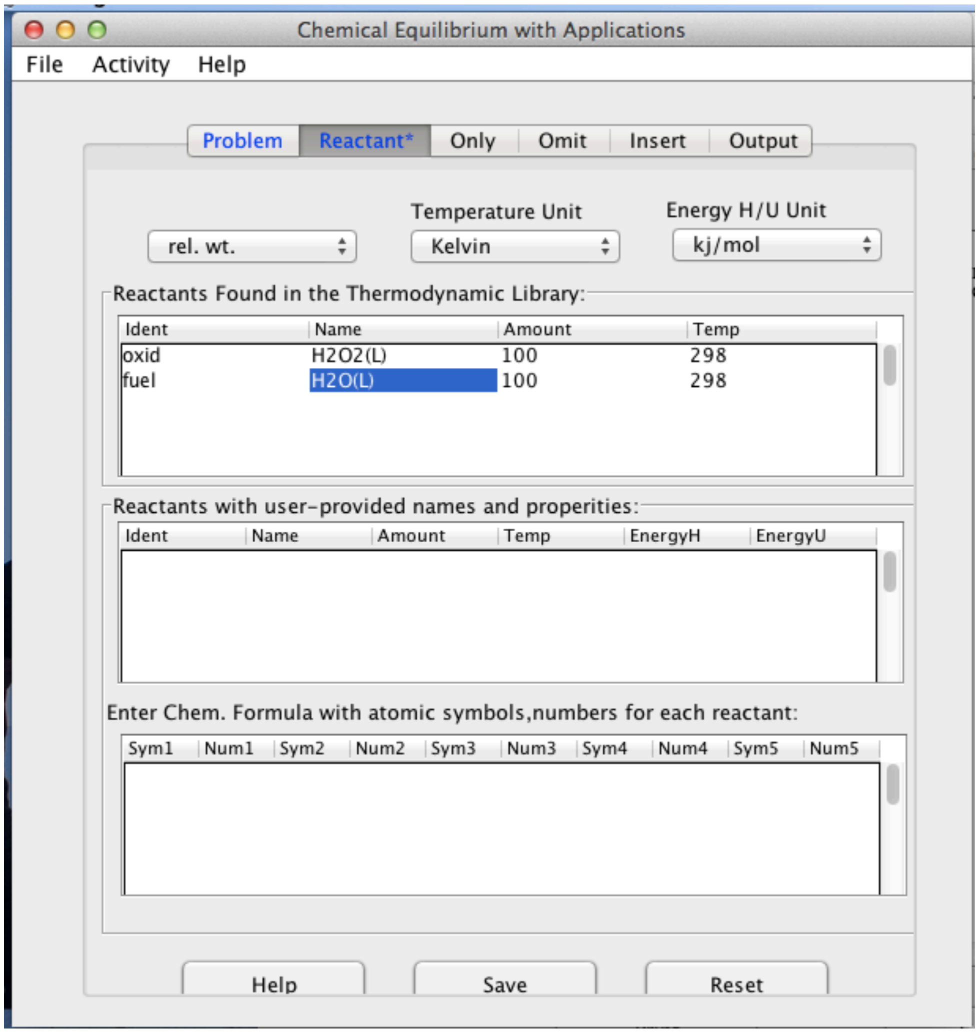
Mechanical & Aerospace Engineering

Part 1): concluded

- **CEA Reactant Setup**



Example Reactant Setup for Monoprop

-100% H_2O_2 as Oxidizer

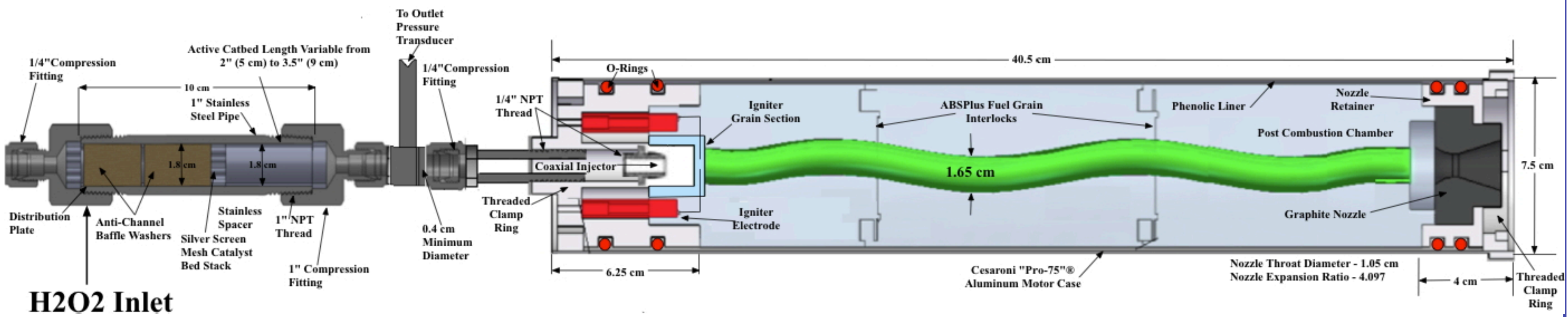
--100% H_2O as “Fuel”

Use Liquid Species for reactants

Part 2 *Peroxide /ABS Hybrid Thruster*

- **Now Look at Upgrading EGC Rocket as H_2O_2/Printed-ABS Hybrid**
- **Peroxide Decomposed using Activated Silver Catalyst Bed**
- **Decomposed Products Injected Into Thrust Chamber and Ignited with ABS Fuel**

Hydrogen Peroxide Catbed Adapter for Arc-Ignition Hybrid Rocket Thrust Chamber with Additively Manufactured ABS Fuel Grain with Helical Port



$$\text{ABS} = \begin{bmatrix} acrylonitrile \\ butadiene \\ styrene \end{bmatrix} = \begin{bmatrix} CH_2 = CH - C \equiv N \\ C_4H_6 \\ C_6H_5CH = CH_2 \end{bmatrix}$$

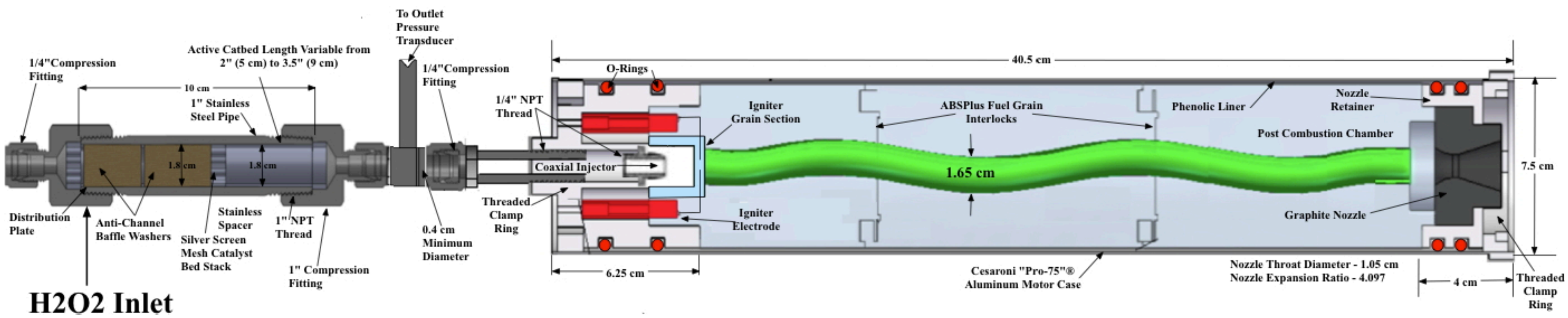
- **Typical formulation consisting of 50% mole fraction butadiene, 43% Acrylonitrile, and 7% styrene monomers.**

- **Reduced Chemical Formula of ABS ..** $(C_{3.85}H_{4.85}N_{0.43})$

Part 2 *Peroxide /ABS Hybrid Thruster* *(2)*

- **H_2O_2/ABS Hybrid**

Hydrogen Peroxide Catbed Adapter for Arc-Ignition Hybrid Rocket Thrust Chamber with Additively Manufactured ABS Fuel Grain with Helical Port



- **For Every Mole of Peroxide Decomposed ½ Mole of Gaseous Oxygen is Released**

$$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2$$

.. Or about 0.47 grams of O_2 for each gram of H_2O_2

ABS enthalpy of formation is calculated as 62.63 *kJ/g-mol*,

So it's presence adds considerably to the available heat

(Part 2): Peroxide /ABS Hybrid Thruster (3)

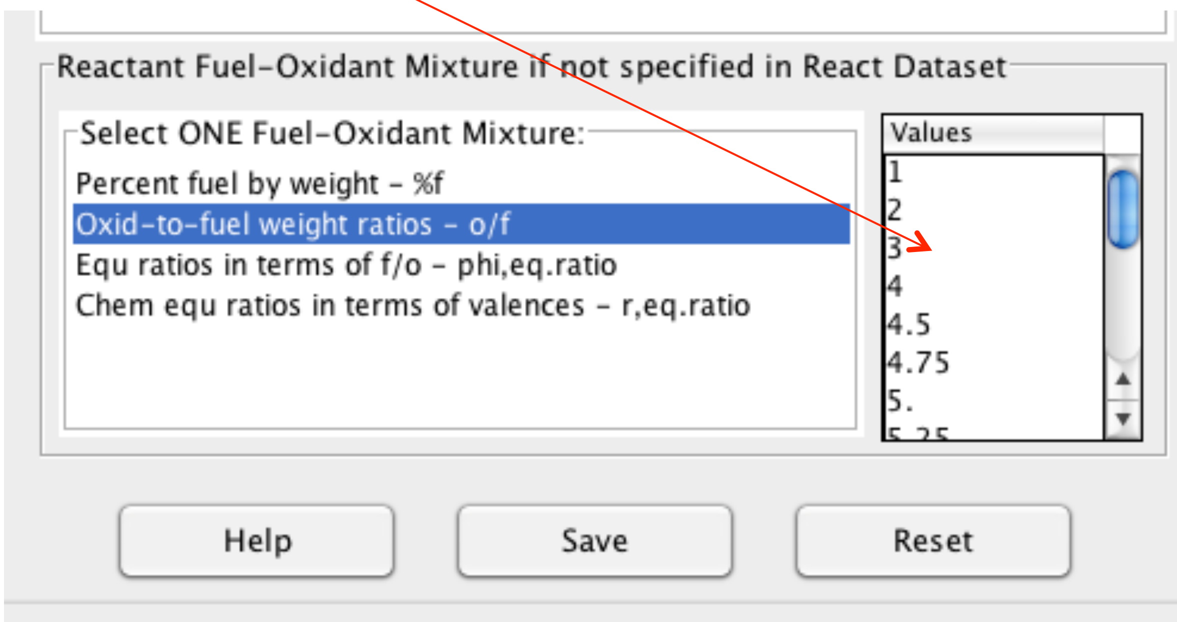
- **Assume the same 5:1 Nozzle expansion ratio nozzle for the EGC engine**
- **Set up input file to run as "Rocket" Problem but now input peroxide and Water as oxidizers and enter ABS data in the User defined input section**
- **Run code in "equilibrium", with "infinite" combustor contraction ratio,**
- **{H_2O_2 H_2O} = "oxidizer", ABS = "fuel"**
- **Use appropriate Oxidizer mass percentages to allow peroxide solutions ranging from 80% to 99%...** ***You will need to perform multiple runs to cover this range***
- **Use CEA to calculate Chamber, throat, and exit properties**
- **Iterating the code .. Find the approximate chamber pressure that gives the optimal performance for sea level operation … i.e. where does the hybrid thrustervExit** ***pressure = 1 atmosphere. (this value may be different than for monopropellant ABS)***
- **Plot the** ***best performance O/F ratio*** **and the values of C* and optimal Isp for that O/F Ratio as a function peroxide concentration (*for each of the data runs*)**

(Part 2): Peroxide /ABS Hybrid Thruster [3]) [4]

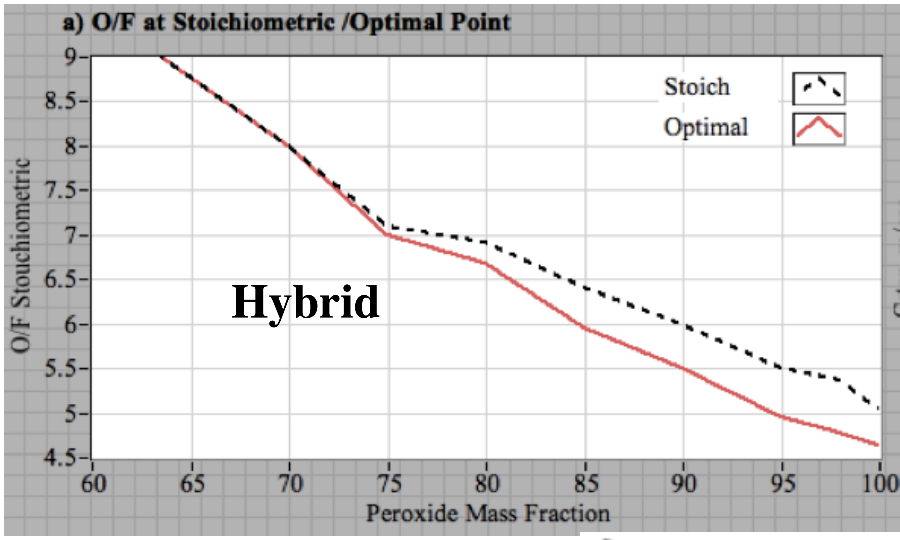
• **Set up problem to calculate performance of Hybrid for O/F varying across "best performance" range of interest**

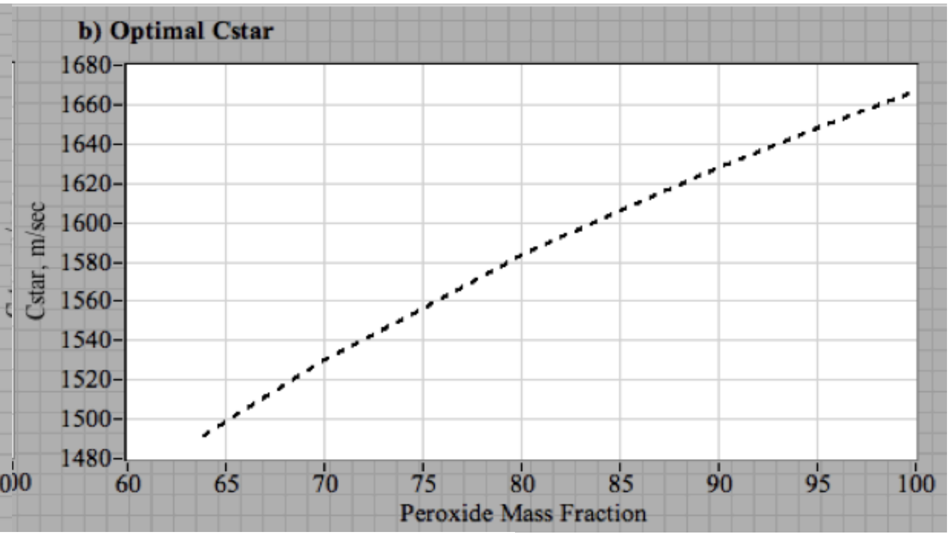
Example

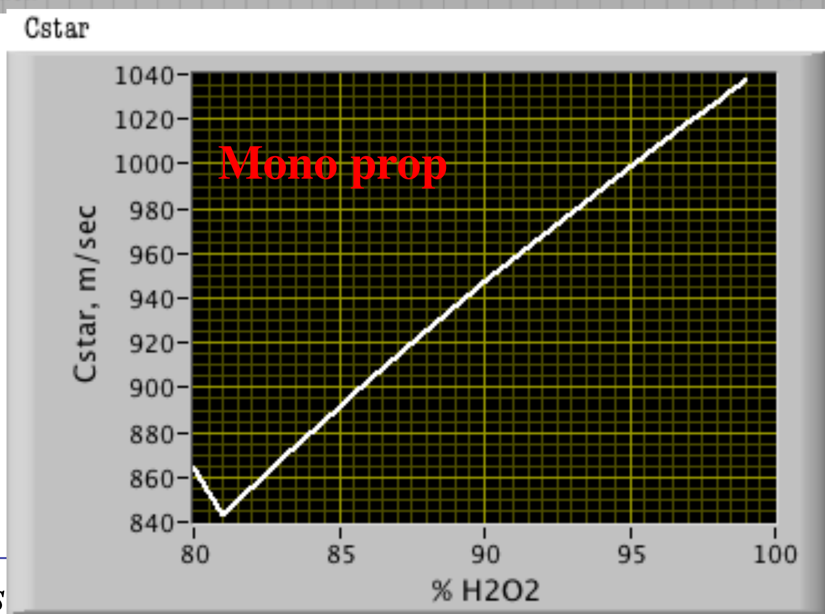
$$O/F = \frac{M_{90\% H_2O_2 + 10\% H_2 0}}{M_{100\% ABS}}$$



(Part 2): Peroxide /ABS Hybrid Thruster (3)) (4)

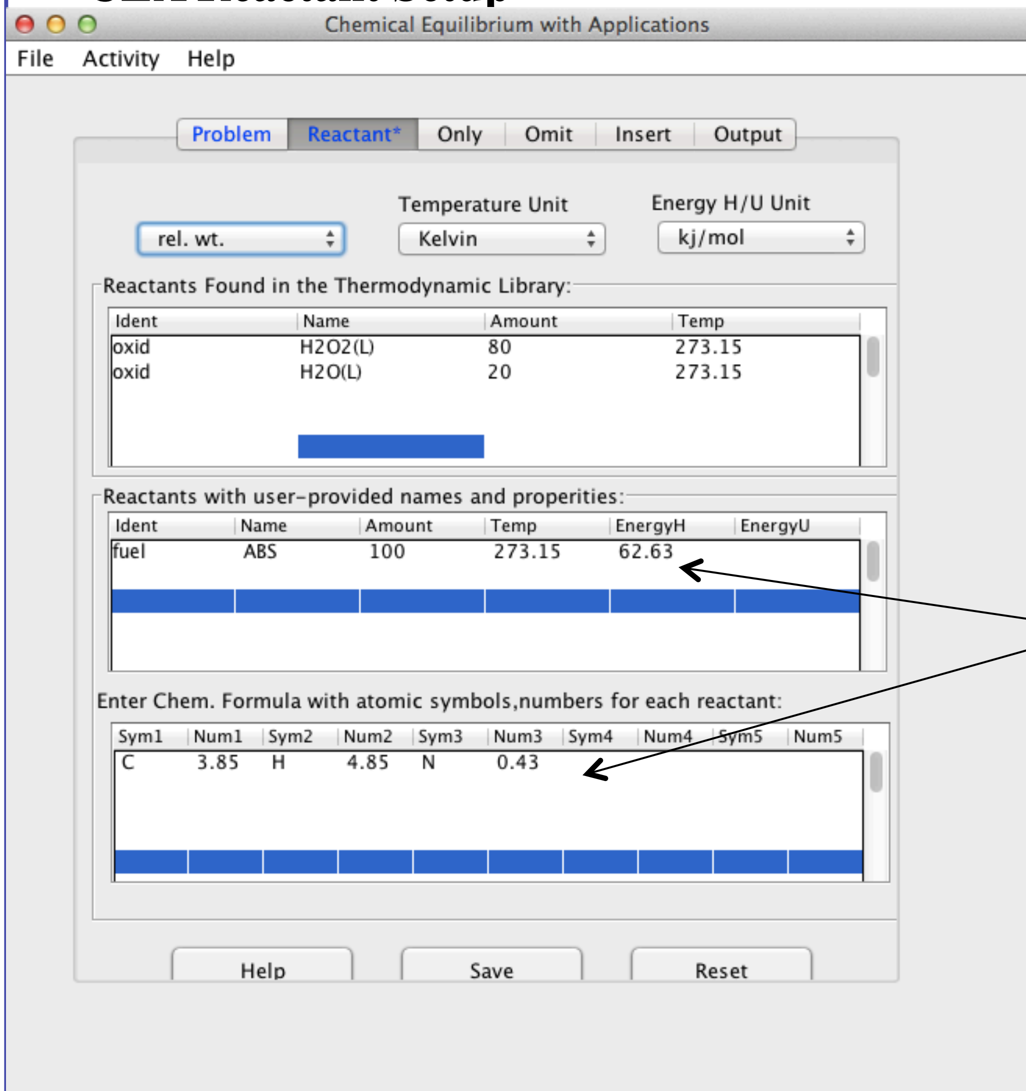






Part 2): concluded

• **CEA Reactant Setup**



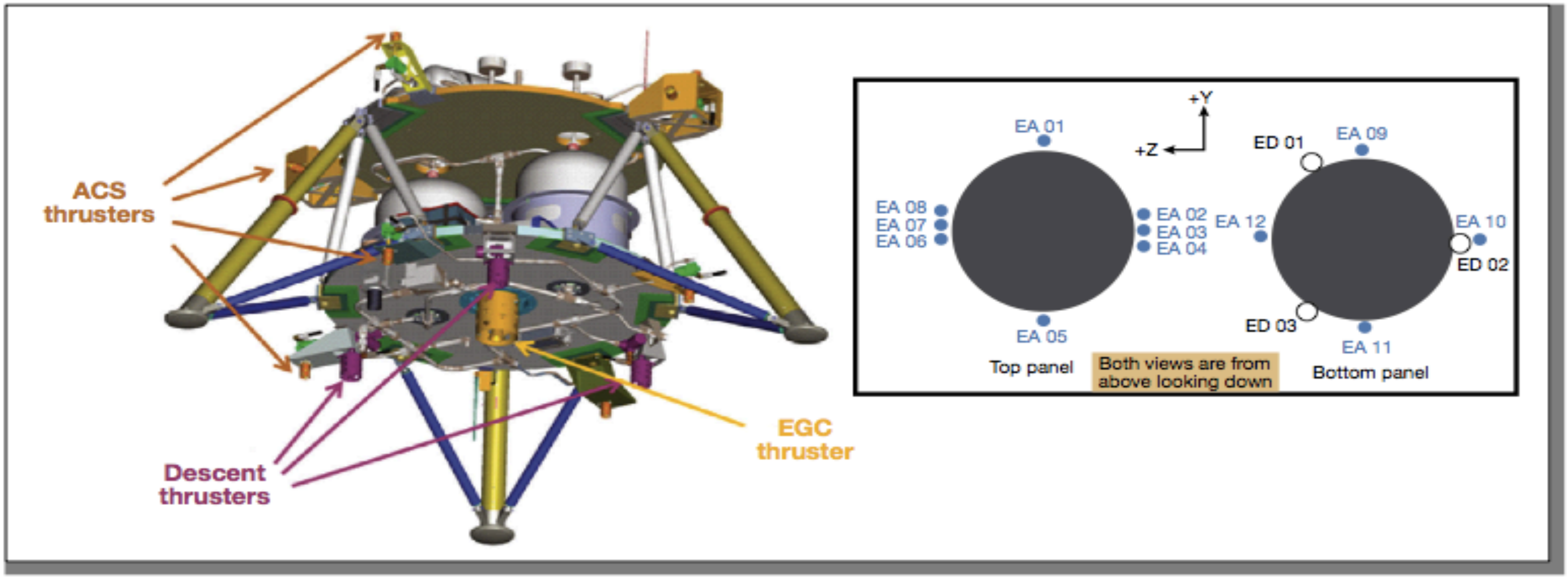
Example Reactant Setup for Hybrid

-80% H_2O_2 as Oxidizer
-20% H_2O as other part of oxidizer

--100% ABS as "Fuel"

User Data Entry Area

Part 3



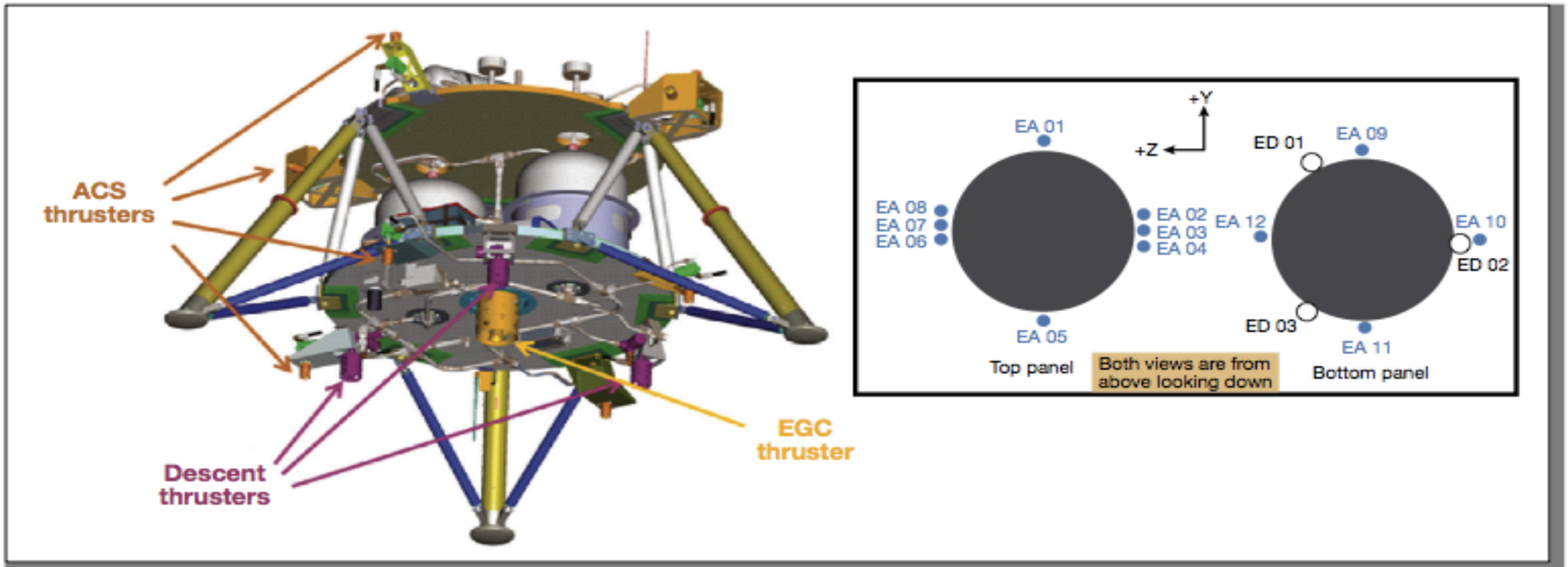
- Because the EGC engine operates continuously and offsets 5/6th of the vehicle weight, the total "Delta V" capacity of the EGC system is the primary driver limiting the vehicle flight time.

Propulsive ΔV loss from acting against gravity....

$$\left(\Delta V\right)_{\substack{gravity\\loss}} = \int_0^{T_{burn}} g(t)\cdot\sin\theta\cdot dt$$

Current flight time ~ 35 seconds

Part 3 (2)



$$Hover \rightarrow \theta = 90^{o} \rightarrow \Delta V = g \cdot t_{hover} = g_0 \cdot I_{sp} \cdot \ln\left(\frac{M_i}{M_f}\right)$$

- **How will an increase in specific impulse affect available flight time (hover time)?**

$$\Delta V = g \cdot t_{burn} = g_0 \cdot I_{sp} \cdot \ln\left(\frac{M_i}{M_f}\right)$$

Part 3 (3)

• How will an increase in specific impulse affect available flight time (hover time)?

• Assume negligible change in vehicle mass fraction …

$$\frac{\Delta V_2 = g \cdot t_{burn_2} = g_0 \cdot I_{sp_2} \cdot \ln\left(\frac{M_i}{M_f}\right)}{\Delta V_1 = g \cdot t_{burn1} = g_0 \cdot I_{sp_1} \cdot \ln\left(\frac{M_i}{M_f}\right)} \rightarrow \left(\frac{t_{burn_2}}{t_{burn1}}\right) = \left(\frac{I_{sp_2}}{I_{sp_1}}\right)$$

• Hover time is directly proportional to Isp ….

• i.e. and two-fold increase in Isp will double available hover time …

• Plot the Ratio of Available Burn Time for (hybrid/monopropellant) based on Best Hybrid Performance O/F ratio as a function of Peroxide mass concentration

• At What Peroxide concentration does the performance of the hybrid equal the 90% monoprop? (if you could get the motor to light?)

Propellant Comparisons

Table 3 Comparison of Monopropellant Costs for FY 06[12]

Monopropellant	Unit Pack	Price Delivered
Hydrogen Peroxide (70%)	40,000 lbm Bulk	\$0.50/lbm
Hydrogen Peroxide (90-99%)	30 gal Drums	\$5.00/lbm Author Info
HAN-Glycine-Water	None	To Be Determined
Hydrazine (100%)	Bulk	\$78.01/lbm
Hydrazine (100%) High Purity	Bulk	\$189.00/lbm
CO2 (Liquefied Gas)	Bulk	\$0.10/lbm
Helium	Cylinder	\$0.45/ft^3
Nitrogen	Bulk - Liquid	\$94.75/Ton

Within the continental U.S., the list price for 50% Technical Grade (standard industrial grade): \$0.345 per lbm

Market Disruptive?