Problem 1.

Consider a spacecraft in a circular LEO at altitude of 200km. Design a system diagram and estimate the mass and volume of a propulsion system to transfer to a circular orbit of altitude 350km. Consider your valving to protect for jet fail on/jet fail cases, as appropriate. Include propellant and N2 pressurant tanks, plumbing, valves, and a single engine for:

(a) Monopropellant (hydrazine)

(b) Bi-propellant (your choice)

The amount of ΔV required for a Hohmann transfer from a 200km to a 350km orbit, under the assumption of instantaneous impulses is

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right),$$

to enter the elliptical orbit at $r = r_1$ from the r_1 circular orbit, and

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1+r_2}}\right),$$

to leave the elliptical orbit at $r = r_2$ to the r_2 circular orbit. For $r_1 = 6571$km and $r_2 = 6721$km, with $\mu = 398600.4 \text{km}^3\text{s}^{-2}$, the total ΔV required is 87.3 m s^{-1}.

Engine	Type	Mass (kg)	Propellant	Thrust (N)	SI (s)
MR-80B	Monoprop	8.5	Hydrazine	3,780	225
R-40B	Biprop	6.8	NTO (MON-3)/MMH	4,000	293

Table 1: Information on the two engines used for this analysis.

To calculate our change in mass, we can use the rocket equation,

$$\begin{aligned}
\frac{M_i}{M_f} &= exp(\frac{\Delta V}{g_0 \cdot \text{ISP}}) \\
\frac{M_{fuel} + M_f}{M_f} &= exp(\frac{\Delta V}{g_0 \cdot \text{ISP}}) \\
M_{fuel} &= M_f\left(exp(\frac{\Delta V}{g_0 \cdot \text{ISP}}) - 1\right),
\end{aligned}$$

which shows that the required ΔV is a function of the initial mass of the craft. For a small satellite with a mass of 500kg, the required mass for fuel is listed in Table 2.

To calculate the volume required for the burn, we can simply calculate $V = m/\rho$. Hydrazine has a density of 1011 kg m^{-3}, and for 20.19 kg of fuel this results in a required volume of 0.0200 m^3. For the bipropellant, we need to mix fuel and an oxidizer at a mass ratio of MON/MMH= 2.16. This results in 10.54 kg of fuel, and 4.88 kg of oxidizer. MON has a density of 1442 kg m^{-3}, and MMH has a density of 880 kg m^{-3}. This results in tank volumes of .0073 m^3 and .0055 m^3, respectively.

Engine	SI (s)	ΔV (kg)	Volume (m^3)
MR-80B	225	20.19	0.0200
R-40B	293	15.43	0.0128

Table 2: Information on the two engines used for this analysis.

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#######################################
#              +-----+                #
#              | Fuel|                #
#              +--+--+                #
#                 |                   #
#              x--+--x                #
#              |     |                #
#              |     |                #
#              |     |                #
#              x--+--x                #
#                 |                   #
#                 |                   #
#                 |                   #
#                 |                   #
#                 +                   #
#                / \                  #
#               /   \                 #
#              /     \                #
#              -------                #
#######################################
#      +-----+         +-----+        #
#      | Fuel|         | Oxid|        #
#      +--+--+         +--+--+        #
#         |               |           #
#      x--+--x         x--+--x        #
#      |     |         |     |        #
#      |     |         |     |        #
#      |     |         |     |        #
#      x--+--x         x--+--x        #
#         |               |           #
#         +-------+-------+           #
#                 |                   #
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#                 +                   #
#                / \                  #
#               /   \                 #
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#              -------                #
#######################################
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Diagram 1: Serial and parallel valve designs for monoprop and bipropellant systems. Each x represents a valve.

Problem 2.

Read "Mission Analysis for a Micro RF Ion Thruster for CubeSat Orbital Maneuvers"

(a) Which propulsion system included in the paper would you choose for a maximum orbit change given mass and volume constraints?

Busek Green Monopropellant 3U

(b) What is the chemical name and estimated ISP for the propellant of the system chosen in a)?

Chemical name: AF-M315E, ISP: 230 s

(c) If you wanted to minimize propellant usage for the circularization burn of a Hohmann transfer, where on the orbit would you burn?

Perigee

(d) For use on a 3U CubeSat, what is the total mass and volume of the thruster, propellant, and tank chosen in a)?

Mass of thruster: < 0.7 kg, Volume of thruster: .0514 U
Mass of propellant: 4.9959 kg, Volume of propellant: 3.3986 U
Mass of tank: 2 kg, Volume of tank: 3.3986 U

(e) What is the nominal thrust level and input power required? Why is input power required at all?

Thrust: 500 mN, Inputer Power: 20 W
Power is required for both the valve, and for preheating. The thrusters have a minimum start temperature.

"Due to the advanced monopropellant thrusters elevated minimum start temperature, catalyst bed preheat power requirements are higher compared to a conventional hydrazine system. This increase is partially offset, however, by the reduced power needs of the thrusters single seat valves, as well as much lower power required for system thermal management during non-operating periods enabled by the propellants demonstrated storage stability very low temperatures (although current CONOPS for the GPIM mission call for the propellant to be maintained within nominal system operating range)." Spores, Ronald A., et al. "GPIM AF-M315E propulsion system." 49th AIAA Joint PropulsionConference (2013).

(f) Why is the propellant you have chosen any better than hydrazine?

The green propellant can be handled without a hazmat suit, and won't kill anyone after accidental exposure. Additionally, AF-M315E offers a 12% higher ISP, and is 45% more dense. Additionally, this fuel cannot freeze, and does not require constant heating.

(g) What is the main reason that you cannot instead use the Aerojet/Rocketdyne MPS-110 Cold-Gas Thruster system for CubeSats?

The MPS-110 is still in development, and is not yet available for purchase.

Problem 3.

Read "Using Additive Manufacturing to Print a CubeSat Propulsion System"

(a) One problem encountered was arcing between a ground wire and the thruster sheath, and of course you worry about thermal containment with a spark-powered thruster in a plastic spacecraft. What would be your recommendation of a less challenging thruster system to study for incorporation into a 3-D printed CubeSat bus? Pros and cons?

As the paper suggests, cold-gas systems are a relatively simple propulsion system which could be studied. Cold-gas thrusters can deliver sufficient ΔV for proximity operations, and would avoid both the arcing and thermal problems present in the spark-powered thrusters. The primary con to cold-gas thrusters is that they require high pressure (up to 2.75 MPa) for most propellants to provide sufficient ΔV when considering blow-down systems. The additive manufacturing process can have difficulty sufficiently sealing parts, however, which is why the authors went with the spark-powered thrusters. The authors *do* note that other researchers have seen success sealing their additively manuafactured parts, so the pressure issue may be overcome through existing techniques.