

Q.1

 $F = 6 \text{ kN}$ Max. acceleration, $a_{\text{max}} = 10g$ Empty mass of vehicle = 40 kg Let M_b = Burn-out mass.Max. acceleration \Rightarrow when the rocket reaches burn-out stage.

$$\frac{F - M_b \cdot g}{M_b} \leq a_{\text{max}}$$

$$\frac{F - M_b \cdot g}{M_b} \leq 10g \Rightarrow F \leq 11 \cdot M_b \cdot g$$

$$\therefore M_b \geq 55.6 \text{ kg}$$

 M_b = Mass of payload (M_L) + Empty vehicle mass \Rightarrow

~~$M_L = 55.6 - 40$~~

$$M_L \geq 15.6 \text{ kg}$$

Payload must be more than 15.6 kg to restrict the acceleration to less than $10g$.

Q2

Payload of satellite mass = 700 kg

stage	M_s	M_p	M_L	M_0	R
Fourth	2200	1200	700	4100	1.41
Third	1400	7000	4100	12500	2.27
Second	8200	40000	12500	60700	2.93
First	25000	140000	60700	225700	2.63

	R_i	I_{s_i}	$u_i = g \cdot I_{s_i} \ln(R_i)$	
Fourth	1.41	304	1024.67	} m/s
Third	2.27	293	2356.31	
Second	2.93	292	3079.36	
First	2.63	264	2504.33	

Total Δu by the vehicle = 8964.67 m/s

Thrust of first stage, $F = 4800$ kN

Total mass of vehicle $M_0 = 225700$ kg

Initial acceleration, $a = \frac{F - M_0 \cdot g}{M_0}$

$$a = 11.45 \text{ m/s}^2$$

$$m \cdot 800 \cdot 0 = 4A$$

$$m \cdot 800 \cdot 0 = 4A \quad \leftarrow \text{ } 800 = 8$$

$$2/14 \cdot 800 = 8 \cdot 4A \cdot 8 = 256$$

$$= 256$$

Q.3

 $P_1 = 6 \text{ MPa} = 60 \text{ bar}$; SG of propellant = 1.75 \Rightarrow

- to nozzle expansion

 $\rho_p = 1750 \text{ kg/m}^3$

Nozzle optimum expansion at 20 km altitude.

$$P_2 (\text{at } 20 \text{ km}) = 101325 \cdot \exp\left(\frac{-h}{8435}\right) \quad \{h \text{ in meter}\}$$

$$P_2 = 9461.78 \text{ Pa}$$

$$\text{Burn rate, } r = 4.5 \times P_1^{0.3} = 15.37 \text{ mm/s} = 15.37 \times 10^{-3} \text{ m/s}$$

$$\text{Burning surface area, } A_b = 1 \text{ m}^2$$

$$\text{Mass flow rate, } \dot{m} = \rho_p \cdot A_b \cdot r = \boxed{26.89 \text{ kg/s}}$$

$$\text{Throat area, } A_t = 0.009 \text{ m}^2$$

$$\text{Characteristic velocity, } c^* = \frac{P_1 \cdot A_t}{\dot{m}} = \boxed{2008.2 \text{ m/s}}$$

Nozzle area expansion ratio, (for $k = 1.2$)

$$\frac{A_t}{A_2} = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \left(\frac{P_2}{P_1}\right)^{\frac{1}{k}} \sqrt{\frac{k+1}{k-1} \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]}$$

$$\frac{A_t}{A_2} = 1.61 \times 4.62 \times 10^{-3} \times 2.69 = 20 \times 10^{-3} = \frac{1}{\epsilon}$$

$$\therefore \boxed{\epsilon = 50}$$

$$R = \frac{R_u}{MW}$$

$$MW = 19$$

$$c^* = \frac{\sqrt{k R T_1}}{k \sqrt{\left(\frac{2}{k+1}\right)^{k+1/k-1}}} \Rightarrow \boxed{T_1 = 3876.31 \text{ K}}$$

$$\text{Gas jet velocity, } V_2 = \sqrt{\frac{2k}{k-1} \frac{R_u}{MW} T_1 \left(1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right)}$$

$$\boxed{V_2 = 3661.97 \text{ m/s}}$$

Ex 4.3) $P = 6 \text{ MPa} = 60 \text{ bar}$; $\rho = 1.75 \text{ of propellant}$

Thrust, $F = \rho_2 \dot{m} v_2$ (optimum expansion at cruise altitude)

$\therefore F = 98.47 \text{ kN}$

Specific impulse $I_{sp} = \frac{F}{\dot{m}g} = 373.9 \text{ sec}$

Drawback of end-burning configuration: —

There is a major shift in the CG (Center of gravity) of the vehicle as the propellant gets consumed.

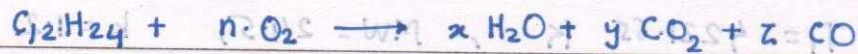
Alternative grain geometry \Rightarrow Star-burning grain.

Suitable thrust vectoring technique \Rightarrow Jet-vane type

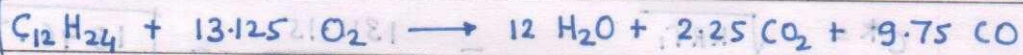
Gas jet velocity, $v_2 = \sqrt{\frac{2 \gamma}{\gamma - 1} \frac{P}{\rho_2} \left(1 - \left(\frac{P_2}{P} \right)^{\frac{\gamma - 1}{\gamma}} \right)}$

$v_2 = 3661.37 \text{ m/s}$

Q4



$$MR = 2.5 = \frac{m_{ox}}{m_F} = \frac{n \times 32}{(144 + 24)} \Rightarrow n = 13.125$$



$$\text{Flame Temperature} \Rightarrow [H]_R = [H]_P$$

$$\text{Reactants} \Rightarrow H = -159 \text{ kJ/mol}$$

Products \Rightarrow

Species	n_i	$\Delta h_{f,i}$	$C_{p,i} (T_{ad} - 298)$
H_2O	12	-241	$0.058 (T_{ad} - 298)$
CO_2	2.25	-390	$0.063 (T_{ad} - 298)$
CO	9.75	-112	$0.037 (T_{ad} - 298)$

$$-159 = -4861.5 + 1.1985 (T_{ad} - 298)$$

$$T_{ad} = 4221.65 \text{ K} = T_{ad}$$

$$\text{Molecular weight, } MW = \frac{12}{24} \times 18 + \frac{2.25}{24} \times 44 + \frac{9.75}{24} \times 28$$

$$MW = 24.5 \text{ kg/kmol}$$

$$\text{Average } C_p = 49.93 \text{ J/mol} \cdot K$$

$$C_v = C_p - R_u = 41.62 \text{ J/mol} \cdot K$$

$$k = \frac{C_p}{C_v} = 1.2$$

$$T_1 = 4221.65 \text{ K}, \text{ MW} = 24.5, \quad k = 1.2$$

$$P_1 = 6 \text{ MPa}, \quad \dot{m} = 200 \text{ kg/s}$$

$$[I_s]_{SL} = 270 \text{ sec}$$

$$[I_s]_{vac} = 300 \text{ sec}$$

$$c^* = \frac{\sqrt{kRT_1}}{k \sqrt{\left(\frac{2}{k+1}\right)^{k+1/k-1}}} = \frac{1310.15}{0.71} = 1846.7 \text{ m/s}$$

$$A_t = \frac{\dot{m} c^*}{P_1} \Rightarrow A_t = 0.0615 \text{ m}^2$$

$$(F)_{SL} = \dot{m} v_2 + (P_2 - P_{SL}) A_2 \quad (F)_{vac} = \dot{m} v_2 + P_2 \cdot A_2$$

$$\textcircled{1} (I_s)_{SL} = -\frac{v_2}{g} + \frac{(P_2 - P_{SL}) A_2}{\dot{m} \cdot g} \quad \textcircled{2} (I_s)_{vac} = \frac{v_2}{g} + \frac{P_2 A_2}{\dot{m} g}$$

Subtracting $\textcircled{1}$ from $\textcircled{2}$

$$(I_s)_{vac} - (I_s)_{SL} = \frac{P_{SL} \times A_2}{\dot{m} \cdot g}$$

$$\therefore A_2 = 0.581 \text{ m}^2$$

$$\text{Nozzle expansion ratio, } \epsilon = \frac{A_2}{A_t} = 9.44$$

$$\text{From nozzle map, for } \epsilon = 9.44 \Rightarrow M_2 \approx 3.5$$

For $M_2 = 3.5$, Exit pressure,

$$P_1 = P_2 \left[1 + \frac{1}{2} (k-1) M_2^2 \right]^{k/k-1}$$

$$\Rightarrow P_2 = 49450.5 \text{ Pa}$$

$$P = 101325 \exp\left(\frac{-h}{8435}\right)$$

$$\Rightarrow h \text{ (for optimum expansion)} = \boxed{6050.94 \text{ m}}$$

Best strategy for engine cooling \Rightarrow Film cooling +
Regenerative cooling

Preferred atomization technique \Rightarrow Shear co-axial atomizer
or Swirl-coaxial atomizer