2023 Guidelines and Assumptions – Rev02

Future revisions will be posted in Module 08 in CANVAS

MAE 640 SFRJ Guidelines and Assumptions

1. Mission Requirements

1.1. Configure fuel grain shape and formulation to achieve maximum range of the vehicle.
1.2. Mission A is a Total Solid Propellant Mission (Data Provided by the Instructor)
1.3. Mission B's are Baseline Missions (Project Assignment's 08PR-B, 08PR-C, 08PR-D)
  1.3.1. Mission B is Baseline Rocket Propulsion (no trajectory, no inlet, Baseline Fuel - P1)
  1.3.2. Mission B1-A is Baseline Trajectory Checkout (trajectory, constant airflow, Baseline Fuel - P1) 1.3.3. Mission B1 -B is Baseline System Checkout (trajectory, inlet, Baseline Fuel - P1)
1.4. Mission C's are Team Design Missions to achieve longest range by changing propellant (Project Assignment 04) formulation, grain design, and nozzle design.
1.5. Air Launch at 33,000 ft. (~10 Km)
1.6. The minimum takeover velocity for ramjet operation is Mach = 2.5
1.7. The mission is complete when Mach number reaches 1.0 as the vehicle decelerates.
1.8. Propulsion system inner radius, R_f , and inner length is the same for all missions
1.9. Assume: horizontal flight with no induced drag from the angle of attack
1.10. Maximum Mach number for any flight is 4.5.
1.11. Review and summarize literature on at least 10 different papers, reports, chapters, or articles on ramjet engines and attaching Annotated Bibliographies in the Final Report.
1.12. . Mission B1 assumes that inlet air stagnation temp is fixed at 900R (500K)
  1.14.1. Use Fuel from Baseline Mission
  1.14.2. Size inlet Area A_1 for mass flow of air o 8.0 lb_m/s at Mach 2.50
  1.14.3. Calculate $T_{0a} = T_{03}$ using $\gamma = 1.404303$
  1.14.4. Calculate P_{03} as shown in Lecture
  1.14.5. Use "AIR (900K)" in CEQUEL to c_4*, $c_{f,vac}$ (We will add CEQUEL functionality to match T_{03} on 08PR-D)
  1.14.6. Use $A_{5,0}$ from Mission B
  1.14.7. Use c_4* efficiency at *4* of 0.95
  1.14.8. Calculate vacuum thrust coefficient and adjust to ambient pressure conditions

2. Solid Propellant Booster (The Booster Information will be Provided by the instructor)

2.1. Propellant Properties

  2.1.1. Propellant Temperature Coefficient, $a_0 = 0.030\ (in/s)[(lb_f/in^2)^{-n}]$
  2.1.2. Propellant Pressure Exponent, $n = 0.35$
  2.1.3. Propellant Temperature Sensitivity, $\sigma_p = 0.001$ -/*F*;
  2.1.4. Propellant Characteristic Velocity, $c^* = 5210\ ft/s$
  2.1.5. Propellant Gas Specific Heat Ratio, $\gamma_{sp}\ \gamma = 1.3$
  2.1.6. Propellant Reference Temperature, $T_{b,0} = 70\ ^oF$
  2.1.7. Propellant Actual Initial Temperature, $T_b = 70\ ^oF$
  2.1.8. Propellant density $\rho_p = 0.065\ lb_m/in^3$

2.2. Chamber Requirements

  2.2.1. Maximum Chamber Pressure, $P_{4,max}$ is 1000 psi (solid propellant boost)
  2.2.2. Maximum Empty Chamber Inner Radius, R_f is 6.00 inches
  2.2.3. Maximum Chamber Inner length for propellant, $L_{0,}$ is 68.00 inches
  2.2.4. Minimum boost propellant initial bore radius, $R_{i,\ min}$ for structural integrity is 2.0 inches.
  2.2.5. Maximum Mach Number in Boost Propellant Port is $M_{port,max}$ is 0.5

3. Solid Fuel Ramjet Properties

3.1. The ramjet fuel is a center-perforated cylinder that only burns on the bore (see dimensions in Baseline Configuration Drawing). It does not burn on the ends.
3.2. Baseline Ramjet fuel, Propellant A, is 90% HTPB/(10% IPDI(ARC))
3.3. Propellant **P1** Burning Rate Equation is $r = \frac{0.104 G_{air}^{0.686} P_c^{0.33} T_{air}^{0.71}}{100^{0.33} 530^{0.71}}$ where r[in/s]; P_c [psia]; and T_c [R]
3.4. Propellant **P1** solid density is 0.0331 lb_m/in^3
3.5. Thermochemical properties: Determined in CEQUEL using equilibrium calculations.

3.6. Ramjet c^* efficiency is 75% to 95%

3.7. Maximum Mach number in SFRJ Propellant Port is $M_{port,max}$ is 0.5

3.8. The properties of c^* and specific heat ratio should be calculated from CEQUEL using "HTPB" and "IPDI(ARC)" fuel and "AIR(500K)" at a chamber pressure of 25 psi and use GAMMA for the specific heat ratio.

3.9. At SFRJ burnout assume that the ram drag is equal to the pressure and momentum thrust (no net thrust). So only aerodynamic drag is operating after SFRJ burnout.

3.10. The SFRJ chamber pressure must always be less than or equal to the chamber recovery pressure at any point in the SFRJ operation.

4. Baseline Vehicle Aerodynamic Properties

4.1. Atmospheric Properties at 33,000 ft. altitude (NASA 1976 Atmosphere)

4.1.1. Ambient Pressure, $P_a = 3.800\ lb_f/in^2$

4.1.2. Ambient air density, $\rho_a = 0.02560\ lb_m/ft^3$

4.1.3. Ambient Temperature, $T_a = 400.987\ R$

4.1.4. Ambient Speed of Sound, $a_a = 981.655\ ft/s$

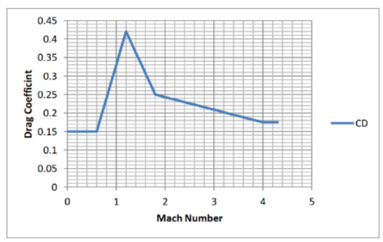
4.1.5. The specific heat ratio of ambient air is 1.404303

4.2. Baseline External Axial Drag Coefficient for Configuration without an Inlet

4.2.1. Assume the drag coefficient is linearly interpolated between points (EXCEL Example)

4.2.2. CD=IF(A2<0.6, 0.15, IF(A2<1.2, -0.12+0.45*A2, IF(A2<1.8, 0.76 -0.283*A2, IF(A2<4, 0.311-0.034*A2, 0.175)))); Where "A2" = Mach Number

Mach Number	Cd
0	0.15
0.6	0.15
1.2	0.42
1.8	0.25
> 4.0	0.175



4.3. Baseline External Axial Drag with an Inlet Included

4.3.1. Baseline Drag Coefficient with a single scoop external inlet during solid boost is assumed 125% of the Drag Coefficient in 4.2 (without an inlet).

4.3.2. Missile Cross Section; $A_{,missile} = 0.92175\ ft^2$ (Based on 13.0-in diameter)

4.3.3. At burnout of the SFRJ, the drag coefficient properties do not change (4.3.1 still applies)

4.4. Baseline Inlet Aerodynamic and Recovery Properties

4.4.1. $P_{0a} = P_a\,[1 + 0.5\,(\gamma - 1)*M_a^2]^{[\gamma/(\gamma-1)]}$

4.4.2. Pressure recovery factor is $[P_{01}/P_{0a}]_{shock} = 1.0 - 0.075\,(M_a - 1)^{1.35}$

4.4.3. The maximum area of air inlet port is 50% of the initial ramjet port area to provide flame holding.

4.4.4. $T_{01} = T_a[1 + 0.5\,(\gamma - 1)*M_a^2]$

4.4.5. $\dot{m}_{air} = \rho_a\, M_a\, a_a\, A_1$

4.4.6. Assume c^* CEQUEL for air is always (**900R, 30 psia**) for the purposes of calculating the inlet mass flow rate (for Design B1, B1-A, and B1-B only)

5. Mass and External Dimensional Properties of Vehicle

5.1. Baseline SFRJ Dimensional Properties

5.1.1. R_i = 3.00 inches

5.1.2. R_f = 6.00 Inches

5.1.3. L_o = 44.00 inches

5.2. BASELINE SFRJ Mass Properties

5.2.1. Takeoff Mass in Baseline Ramjet Configuration: includes the following:

5.2.1.1. Inlet mass, m_{inlet}

5.2.1.2. Booster Propellant Initial Mass, $m_{\mathrm{BP,o}}$

5.2.1.3. SFRJ Initial Propellant Mass, $m_{SFRJ,o,}$

5.2.1.4. Mass of the structure, $m_{\mathrm{struc.}}$

5.2.1.5. and Mass of the Payload, m_{pl}

5.2.2. Mass of Inlet Hardware, m_{inlet}= 20 lb_{m}

5.2.3. Boost Propellant Initial Mass, $m_{\mathrm{BP,o}}$ is initial volume of Boost Propellant time density of Boost propellant (See Figure 1 for configuration)

5.2.4. SFRJ Propellant Initial Mass, $m_{\mathrm{SFRJ,o}}$.is the initial volume of SFRJ Propellant time density of SFRJ propellant (See Figure 1 for configuration)

5.2.5. The mass of the structure is 159.14 lb_{m}

5.2.6. The mass of the payload is 220.00 lb_{m}

5.3. Baseline All Solid Mass Properties

5.3.1. Takeoff mass, m_o is the mass of the structure, $m_{\mathrm{struc.}}$, plus m_{PL} + the solid propellant mass, $m_{\mathrm{p,o}}$.

5.3.2. The instructor will provide final mass properties in the Project Report template.

6. Nozzle(s)

6.1.1. Maximum Exit Area of Nozzle: A_5 = 0.7845 ft^2

6.1.2. Assume: Nozzle Exit Area does not Erode

6.1.3. Nozzle throat diameter erosion is based on $d_{5,t+1} = d_{5,i} + 0.000087 * (t_{t+1} - t_i) * P_{04,i}$ where pressure is in lb_f/in^2 and d_5 is the nozzle diameter in inches.

6.1.4. Thrust coefficient is based on CEQUEL-calculated vacuum I_{sp}, c*, and P_a/P_c adjustment

6.1.5. Minimum thrust coefficient for flow separation is based on P_e/P_a < 33%

6.1.6. The throat area can be instantly enlarged, and the area ratio changed at the beginning of the SFRJ operation to be best suited for the lower pressure combustion.

6.1.7. The area ratio of the nozzle must always be greater than or equal to 1.0 so if erosion causes the throat to grow past the size of the initial exit area, the exit area must be enlarged to keep the throat area ratio at 1.0

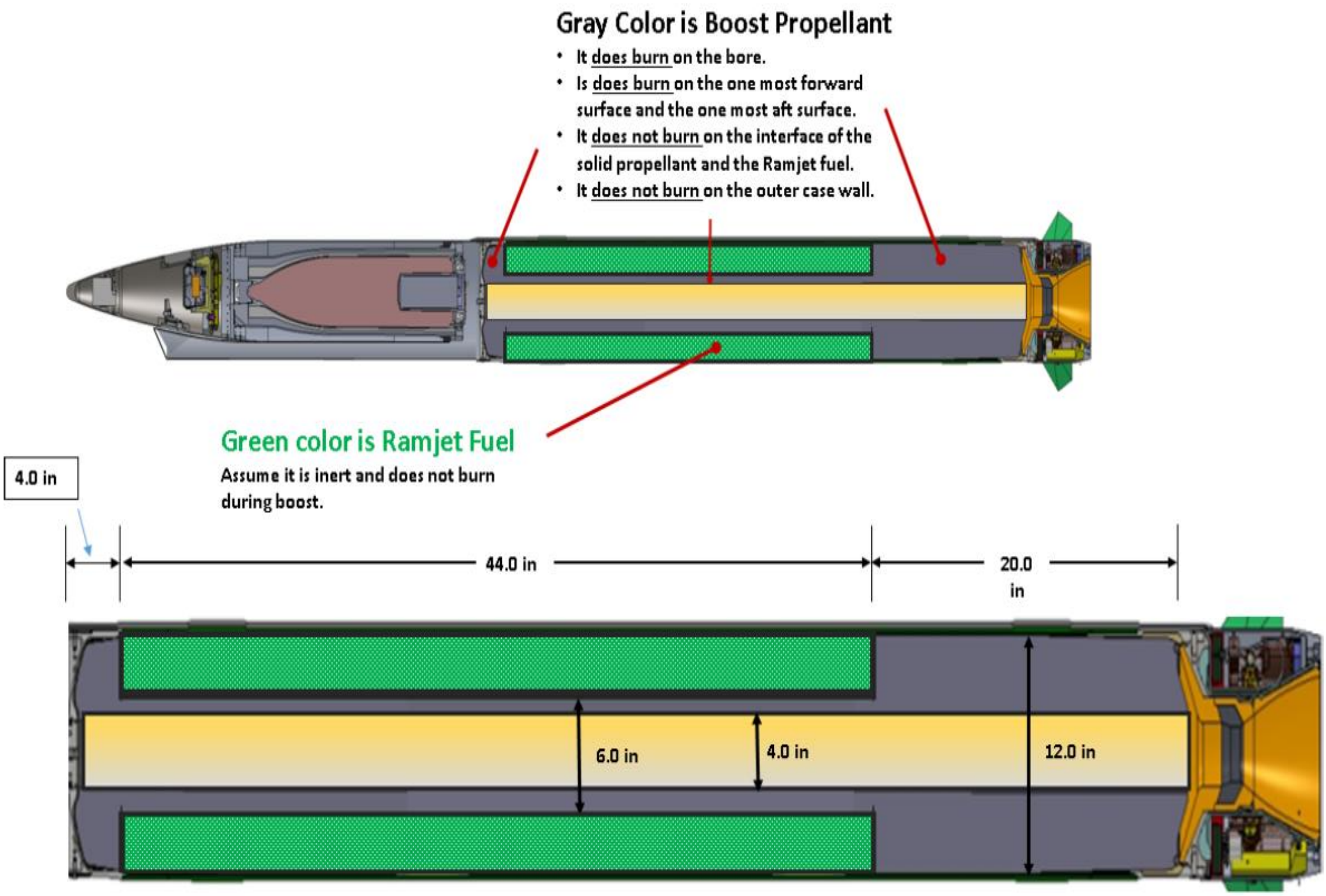


Figure 1 – Baseline Solid Propellant Boosted Solid Fuel Ramjet **for Mission B1 and B2**

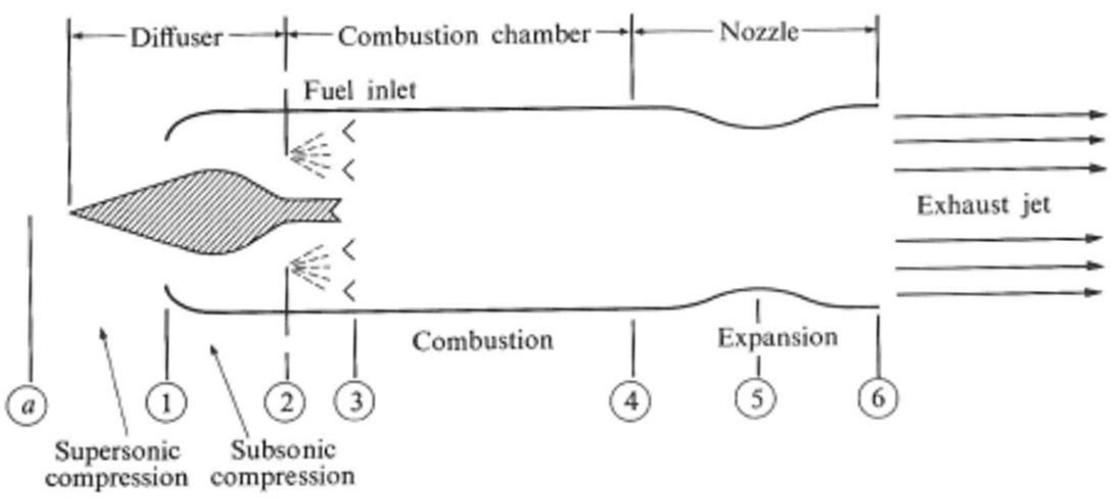


Figure 2. – Ramjet Cycle Station Numbering System

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Table 1. Propellant Formulations

Fuel Ingredients	CEQUEL PROP	Prop.	Prop.	Prop.	Prop.	Prop.
		P1	P2	P3	P4	P5
HTPB	HTPB	90%	63%	63%	63%	81%
IPDI (ARC)	"IPDI (ARC)"	10%	7.0%	7%	7%	9%
Aluminum "AL (S)"	AL (S)	0	30.0%	0	0	0
Boron	"B"	0	0%	30%	0	0
Boron Carbide	"B4C"	0	0	0	30%	0
Magnesium	"MG"	0	0	0	0	10%

Oxidizer Ingredients	CEQUEL PROP	P1	P2	P3	P4	P5
AIR (500K)	AIR (500K)	100%	100%	100%	100%	100%
AIR #	AIR #	100%	100%	100%	100%	100%