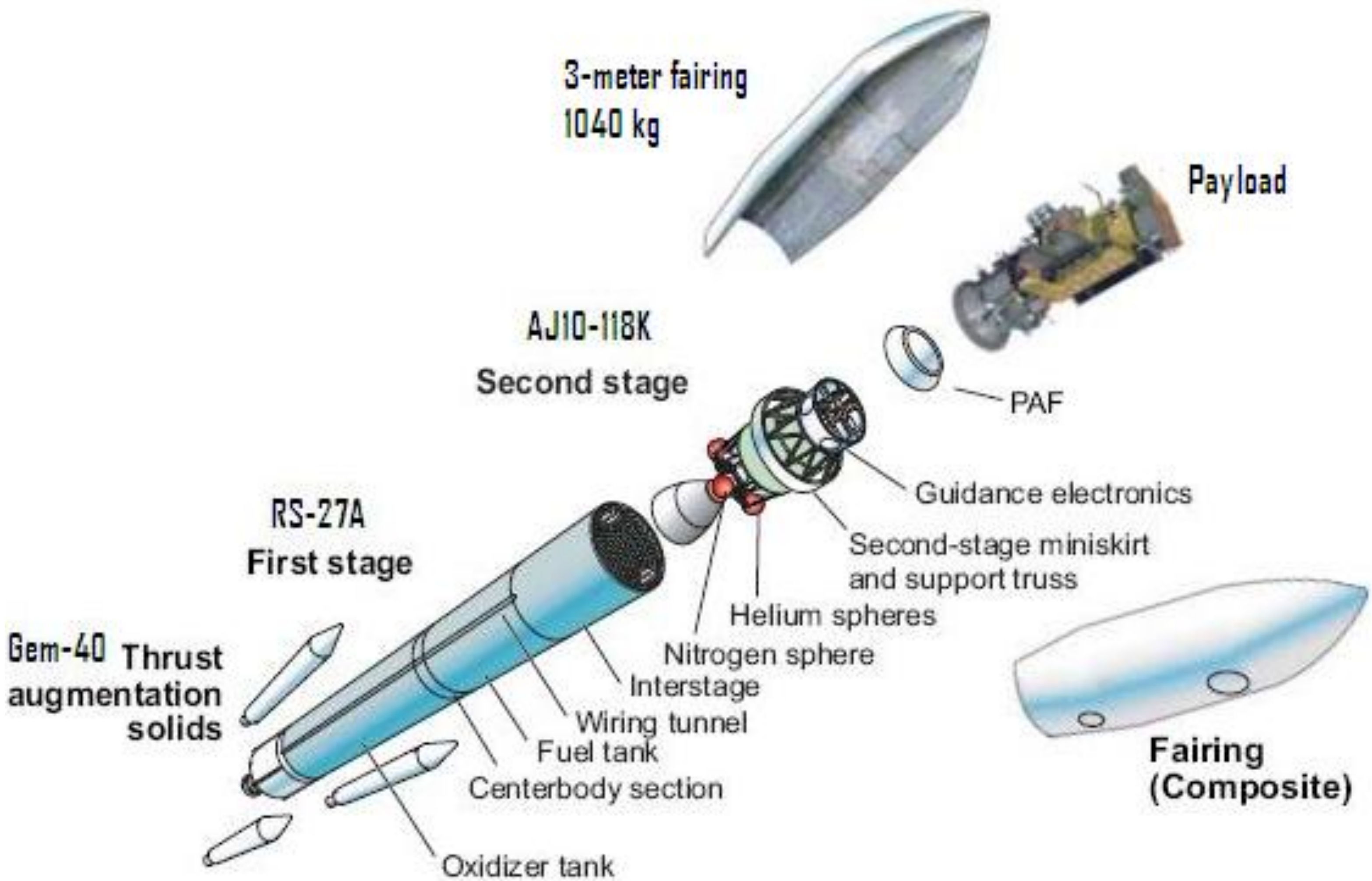
Homework 3, part 1

Delta II 7320 Launch Vehicle



A four digit designator has been used to distinguish between Delta configurations since the early 1970s. However, Boeing uses a new designation system for the Delta IV vehicles. The Delta III is currently available in only one configuration, and thus its four digit designator is rarely used. The Delta IV is available in two basic types, Medium and Heavy. These are designated DIV-M and DIV-H. The Medium can be enhanced ("Medium-Plus") with a larger fairing and strap-on boosters. These configurations are designated with a digit for the fairing diameter in meters, and digit for the number of strap-on boosters. Thus, the DIV-M+ (4,2) has a 4-m fairing and two strap-on boosters, while the DIV-M+ (5,4) has a 5-m fairing and four strap-on boosters.

Example

Delta 7925-10

First Digit

First-stage type, engine type, strap-on motor type

- 0: Long tank, MB-3 engine, Castor II
- 1: Extended long tank, MB-3 engine, Castor II
- 2: Extended long tank, RS-27 engine, Castor II
- 3: Extended long tank, RS-27 engine, Castor IV
- 4: Extended long tank, MB-3 engine, Castor IVA
- 5: Extended long tank, RS-27 engine, Castor IVA
- 6: Extra extended long tank, RS-27 engine, Castor IVA
- 7: Extra extended long tank, RS-27A engine, GEM-40
- 8: Delta III shortened first stage, RS-27A engine, GEM-46

Second Digit

Number of strap-on motors (3,4,6, or 9)

Third Digit

Second-stage engine

- 0: AJ-10-118 (Aerojet)
- 1: TR-201 (TRW)
- 2: AJ-10-118K (Aerojet)
- 3: RL10B-2 (Pratt & Whitney)

Fourth Digit

Third-stage motor

- 0: No third stage or unspecified
- 3: TE-364-3
- 4: TE-364-4
- 5: PAM-D derivative Star 48B
- 6: Star 37FM

Dash Number

Fairing type (optional)

- None: Standard fairing (9.5 ft for Delta II)
- -8: 8-ft fairing
- -10: 10-ft composite fairing
- -10L: 10-ft stretched composite fairing

Reference material

International Reference Guide to Space Launch Systems, 4th ed., Stephen J. Isakowitz, Joseph P. Hopkins, Jr., and Joshua B. Hopkins, American Institute of Aeronautics and Astronautics, Reston, VA, 2003. ISBN: 1-56347-591-X

Stage 1 Properties

- Boeing Delta II Rocket…Stage 1
  - Sea Level Thrust: 890kN
  - Vacuum Thrust: 1085.8 kN
  - **Nozzle Expansion Ratio: 15.25:1**
  - **Conical Nozzle, 30.5 deg exit angle**

- Combustion Properties:
  (RS-27A Rocketdyne Engine)
  - Lox/Kerosene, Mixture Ratio: 2.24:1
  - **Chamber Pressure (P_0): 5161.463 kPa**
  - Combustion temperature (T_0): 3455 K
  - γ = 1.2220
  - $M_W = 21.28$ *kg/kg-mol*

- Propellant Mass: 97.08 Metric Tons
- Stage 1 Launch Mass: 101.8 Metric Tons

Gem 40 Augmentation Rocket Properties (NGC_ATK)

- 3 Boosters Total – Ground Lit
  - Sea Level: 499.20kN
  - Sea Level Vacuum Thrust: 442.95 kN
  - **Nozzle Expansion Ratio: 10.65:1**
  - **Conical Nozzle, 20 deg exit angle**
- Combustion Properties: (Gem 40)
  - Ap/Aluminum/HTPB
  - **Chamber Pressure (P_0): 5652.66 kPa**
  - Combustion temperature (T_0): 3600 K
  - γ = 1.2000
  - M_W = 28.15 *kg/kg-mol*
- Propellant Mass (Each): 11,765 kg
- Launch Mass: 13,080 kg

Stage II Properties

- Boeing Delta II Rocket…Stage 2 AJ10-118 Aerojet Engine

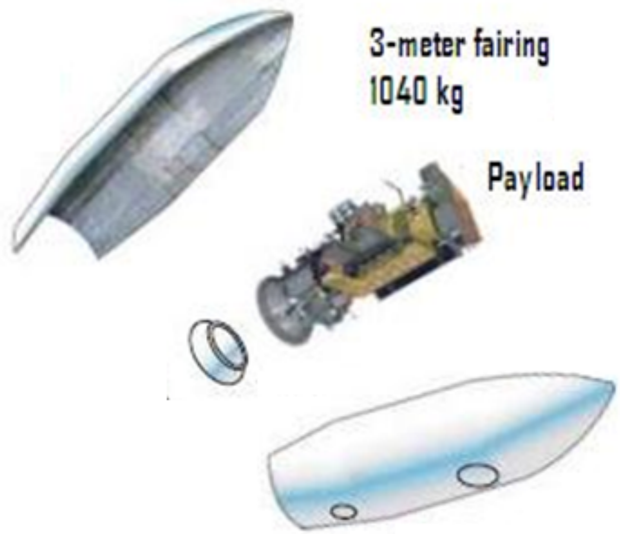
Propellants N_2O_4/Aerozine 50

- Vacuum I_{sp}: 319 seconds
- Vacuum Thrust: 43.657 kN
- Chamber Pressure: 5700 kPa
- Mixture Ratio: 1.8:1
- Nozzle Expansion Ratio: 65:1
- Bell nozzle, exit angle ~ 0 deg.

- Propellant Mass: 6004 kg
- Stage 2 Launch Mass: 6954 kg

Stage III Properties

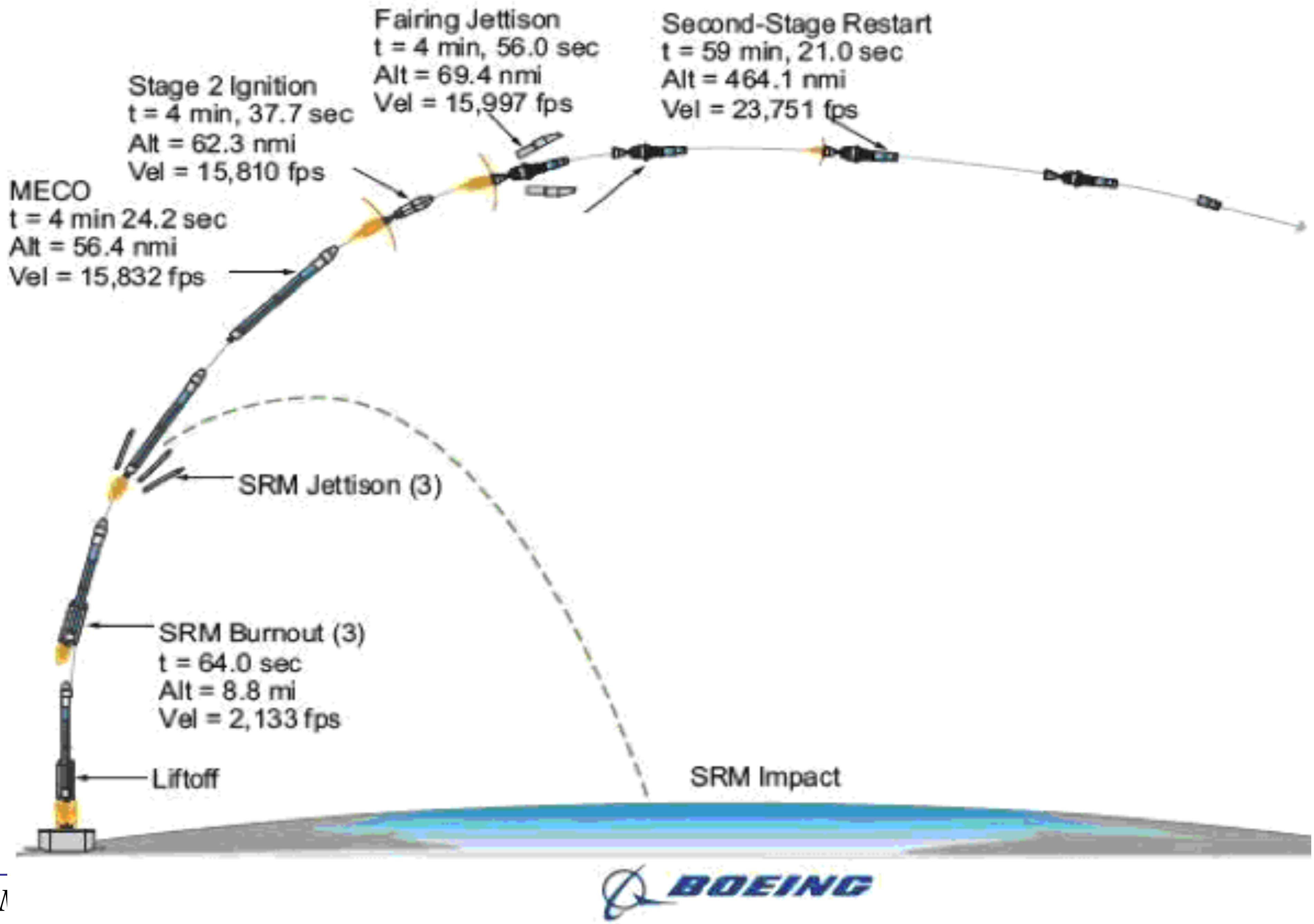
- Payload Inside of 3 meter (10 ft) shroud



- Payload Delivered to Orbit by stages 1-2 (no Kick motor burn)

- Shroud jettisoned prior to reaching orbit
  3-meter Shroud weight ~ 1040 kg

Launch Profile



Problem Objectives (1)

• Estimate Total Payload mass that can be delivered to a 464.1 *nmi* (860.06 km) LEO orbit at inclination 28.7 ° … KSC Launch Due East

• Assume that all gravity losses occur while stage 1 (RS-27A) is burning and the vehicle flys ***"straight up"*** while Gem 40's are burning and then at ***30 deg pitch angle*** for remainder of RS-27A burn

$$\left[(\Delta V)_{\substack{gravity \\ loss}}\right]_{stage} \approx \left[\frac{2}{3}\cdot g_{(h_{initial})} + \frac{1}{3}\cdot g_{(h_{initial})}\right]\cdot \sin\theta \cdot T_{burn}$$

$$..use...g_{(h)} = \frac{\mu}{R^2}..gravity\ \text{model}$$

• Assume no gravity losses during stage 2 burn ..

Problem Objectives (2)

• Estimate Total Payload mass that can be delivered to a 464.1 *nmi* (860.06 km) LEO orbit at inclination 28.7 ° … KSC Launch Due East

• Assume 3% kinematic ΔV losses due to drag (includes interference from GEM 40 Boosters) During the stage 1 burns

$$\Delta V_{drag} = 0.03 \cdot g_0 \cdot I_{sp} \cdot \ln\left(\frac{M_{initial}}{M_{final}}\right)_{stage}$$

• Assume 1040 kg (2.9 meter) shroud + adapter weight

(not budgeted as part of payload) …. Jettisoned during stage 2 burn

• ***(be sure to account for conical nozzle exit thrust losses)***

Problem Objectives (3)

- 1) Calculate … total required delta V for the mission

… be sure to include

a) Required Orbital Velocity

b) Change in Potential Energy

c) Local Earth Rotational Velocity

2) Compare required delta V to available delta V … for each stage

… sure to account for

a) mass changes due to stage separation

b) gravity and drag losses during stage 1 burn

c) shroud jettison 4 min and 56 seconds into burn

You are going to have to iterate the payload weight until

"Available Delta V" = "Required Delta V"

Mission Requirements

- First establish Delta V requirements

Calculate

a) Final Orbital Velocity
b) "Boost Velocity" from earth along direction of launch
(use true local Earth radius at 28.7 deg latitude here)
c) Kinematic Delta V ($V_{orbital}$-V_{boost})
d) Gravitational Potential Delta V
e) Total Delta V

Calculate Stage 1 Booster properties Next

- Need calculations of Mass flow, exit conditions to analyze altitude effects on performance

… Stage "1a"

- 3 x Gem 40 + Stage 1 (RS-27A)

-- Gem 40 Burnout Altitude ~ 8.8 *nmi* (16.31 km)

-- Calculate:

i) Total Lift off Thrust

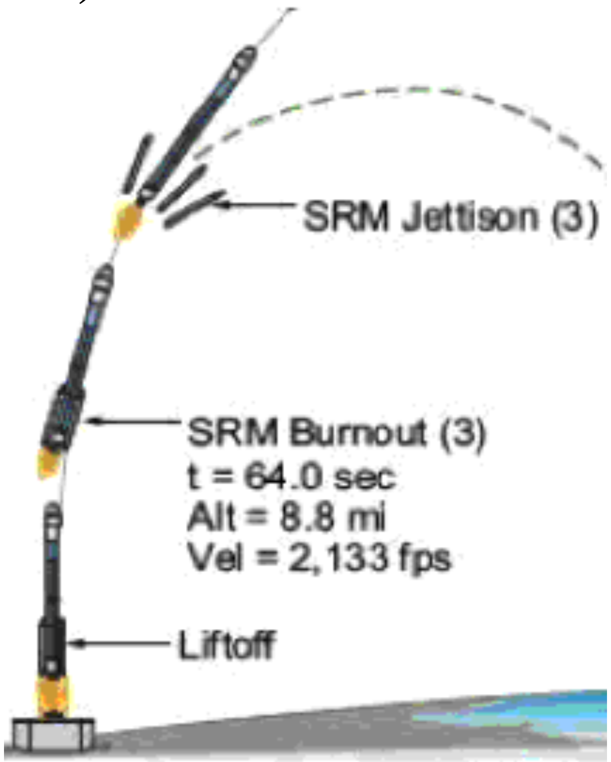
ii) Burn Time for Gem-40(s)

iii) Plot total Thrust profile during Burn "1a" vs Altitude

iv) Total propellant consumed during "stage 1a" burn

vi) Effective Specific Impulse (3 x Gem 40 + RS-27A over operating altitude range

vii) Stage masses at Gem40 burnout



$$Use \rightarrow \left(I_{sp}\right)_{eff} = \frac{2}{3}\left[\left(I_{sp}\right)_{\substack{Rs-27A+\\3x\ Gem40}}\right]_{launch} + \frac{1}{3}\left[\left(I_{sp}\right)_{\substack{Rs-27A+\\3x\ Gem40}}\right]_{\substack{Gem40\\Burnout}}$$

… Stage "1b"

Stage 1 (RS-27A) burning from Gem 40 Burnout Altitude ~ 8.8 *nmi* (16.31 km) to MECO altitude, 56.4 *nmi* (105.52 km)

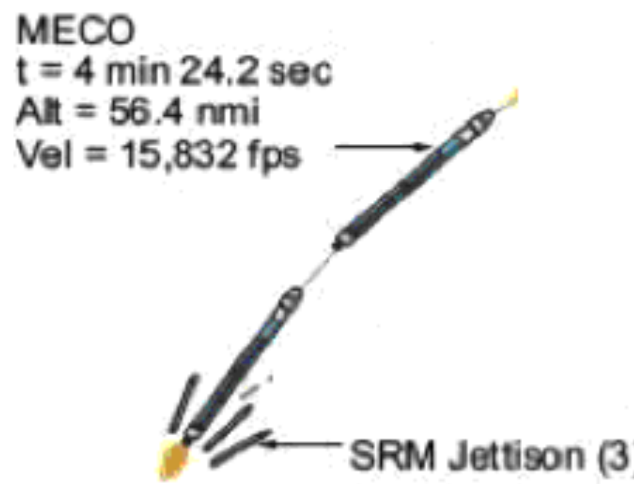
-- Calculate:

i) Burn Time from Gem-40(s) burnout to MECO

ii) Plot thrust profile during "1b" burn vs altitude

iii) Total propellant consumed during "stage 1b" burn

iv) Effective I_{sp} ***Over Altitude Range (16.31 km to 105.52 km)***

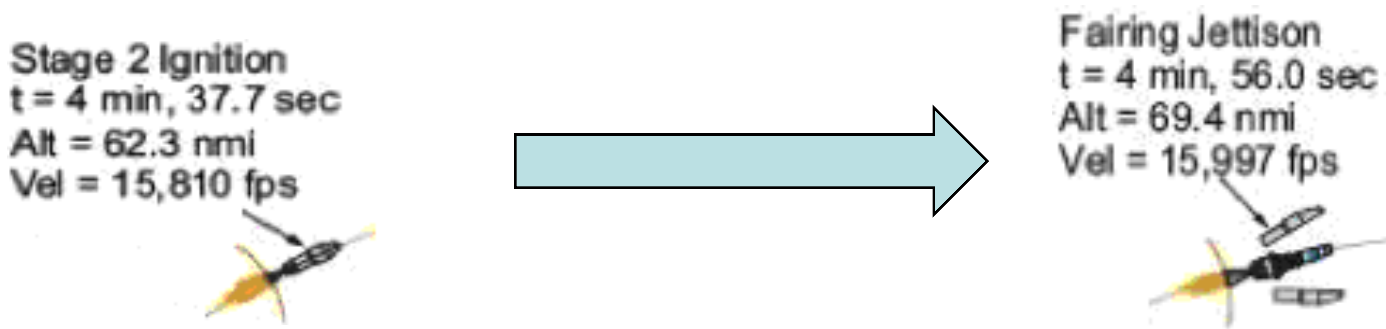


… Stage "2a"

Stage 2 (AJ10-118K Aerojet Engine) burning ignition (4 min 37.7 sec) to fairing jettison (4 min 56 sec) … Altitude ~ 62.3 *nmi* (115.45 km) to 69.4 *nmi* (128.61 km)

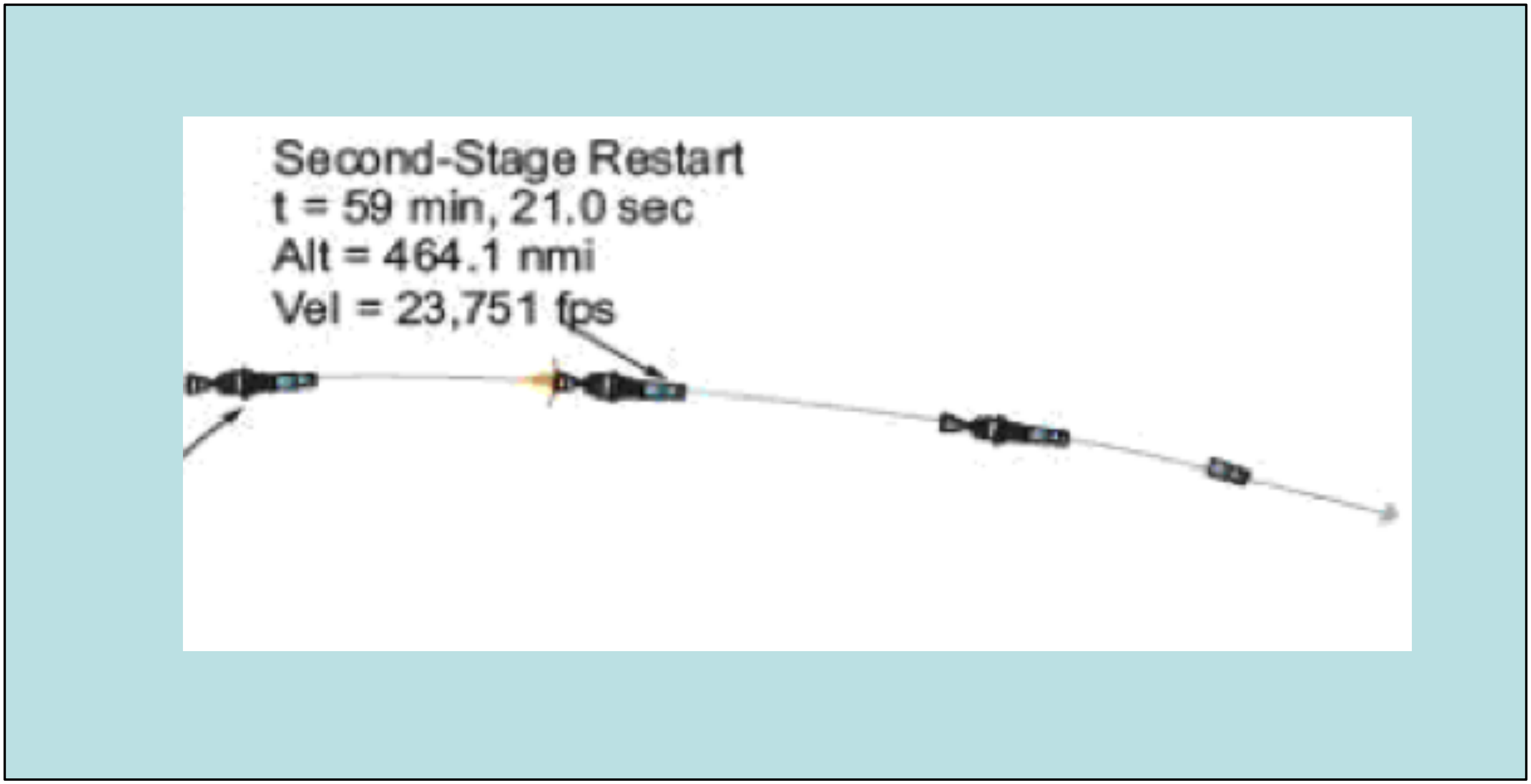
-- Calculate:

i) Stage "2a" massflow
ii) Stage "2a" burn time
iii) Total propellant consumed during "stage 2a" burn
iv) Initial Stage "2a" mass
v) Stage 2a "final mass" before shroud jettison
vi) Final Stage "2a" mass after shroud jettison



… Stage "2b"

Stage 2 from Fairing Jettison to SECO … assume all propellant is consumed in stage



… Stage Mass Fractions

For an assumed payload mass …. Calculate

i) Gross $\frac{M_{initial}}{M_{final}}$ for each "stage" … includes stuff each stage lifts

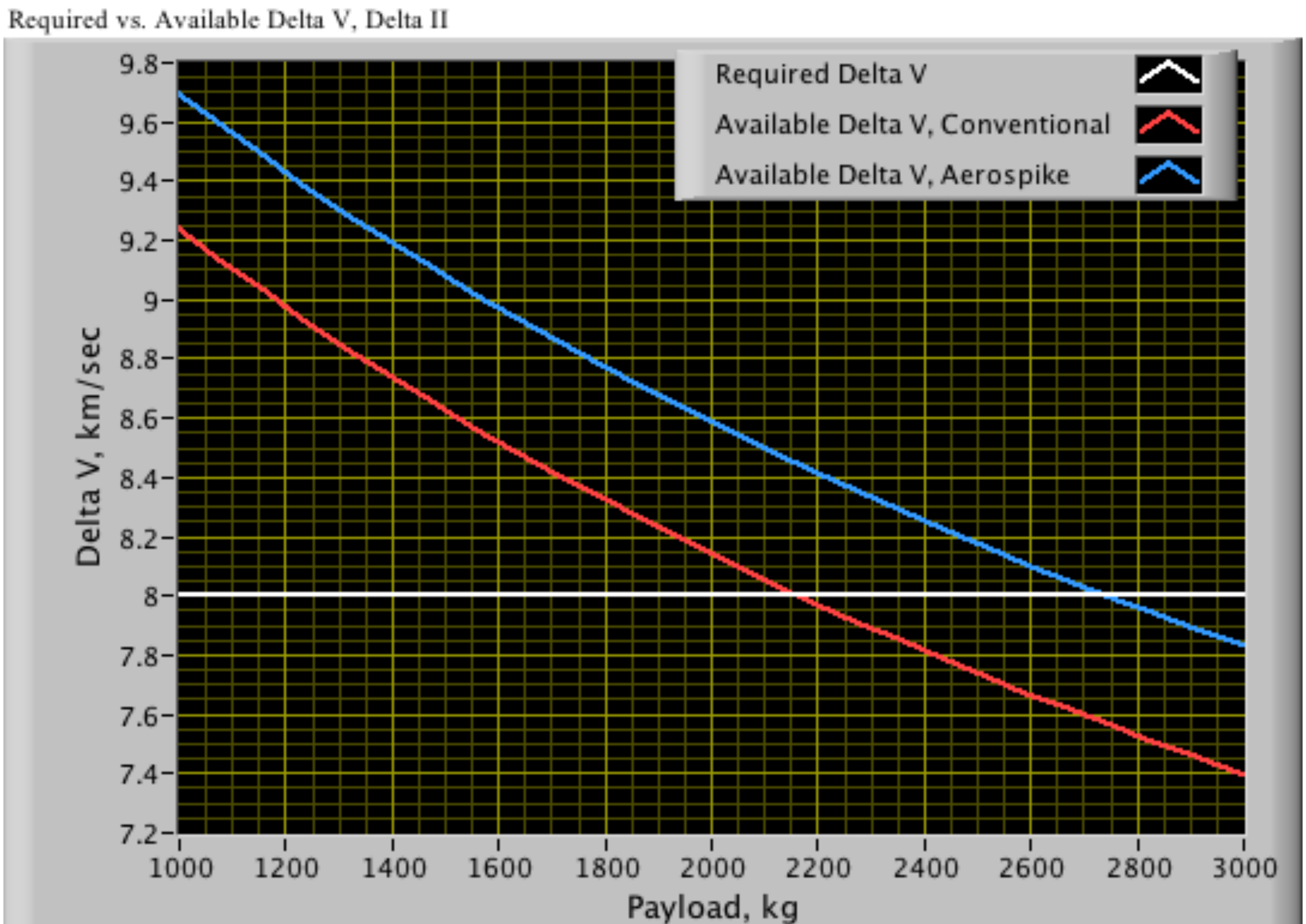
ii) ΔV For each "stage" (include gravity and drag losses .. Where appropriate ***(hint: work backwards from stage "2b")***

iii) Total available ΔV

iv) Compare to $\Delta V_{available}$ *to* $\Delta V_{required}$

………… iterate until you get match

Required versus Available Delta V



Homework 3, Part2

a) Re-derive the Conical (3-D) Aerospike Contour Design Rules (*Slide 31)* for a two dimensional (Linear) Nozzle

b) For Aerospike Nozzle use Sonic Throat section, assume axi-symmetric design, full spike length .. For Aerospike Nozzle use Sonic Throat section, assume axi-symmetric …. design, full spike length .. Design a Conical *aerospike nozzle replacement* for the RS-27A Nozzle (Delta II Stage 1)

... *i) First Compare RS-27A Nozzle Length with minimum length nozzle of same expansion ratio (assume conical nozzle with* 15.25:1 expansion ratio but actual RS-27 A θ_{exit} = 30.5 deg.) …. *Plot both minimum Length and RS-27A Contours*

... *ii) Calculate and plot design Aerospike spike contour of same expansion ratio as RS-27A NOZZLE*

... *iii) Calculate design altitude for this expansion ratio and plot design Mach number and pressure profile along spike LENGTH*

... *iv) Plot delivered Thrust and I_{sp} as a function of altitude for RS-27A ACTUAL, RS-27A MINIMUM LENGTH (CONICAL), AND AEROSPIKE NOZZLE*

$$\theta_{MAX_{RS-27A}} = \frac{\nu_{EXIT}}{2}$$

assume chamber properties identical to RS-27A

Homework 3 cont'd

2) For Aerospike Nozzle use Sonic Throat section, assume axi-symmetric design, full spike length .. For Aerospike Nozzle use Sonic Throat section, assume axi-symmetric …. design, full spike length .. Design a Conical *aerospike nozzle replacement* for the RS-27A Nozzle

... iv) Plot delivered Thrust and I_{sp} as a function of altitude for RS-27a Stage

stage 1a: 0 to 16.31 km altitude (RS-27A + 3 x Gem40)

stage 1b: 16.31 km altitude 105.52 km altitude (RS-27A)

Aerospike Replacement

... Assume conventional Nozzles for Gem-40 boosters, full aerospike for RS-27A

Aerospike Replacement

Homework **1.3, pg3**

... iv) Calculate mean I_{sp} over the operating range of the First stage (use above generated data) Use "2/3rds" rule

Stage "1a"

$$Use \rightarrow \left(I_{sp}\right)_{eff} = \frac{2}{3}\left[\left(I_{sp}\right)_{\substack{Rs-27A+\\3x\ Gem40}}\right]_{launch} + \frac{1}{3}\left[\left(I_{sp}\right)_{\substack{Rs-27A+\\3x\ Gem40}}\right]_{\substack{Gem40\\Burnout}}$$

Stage "1b"

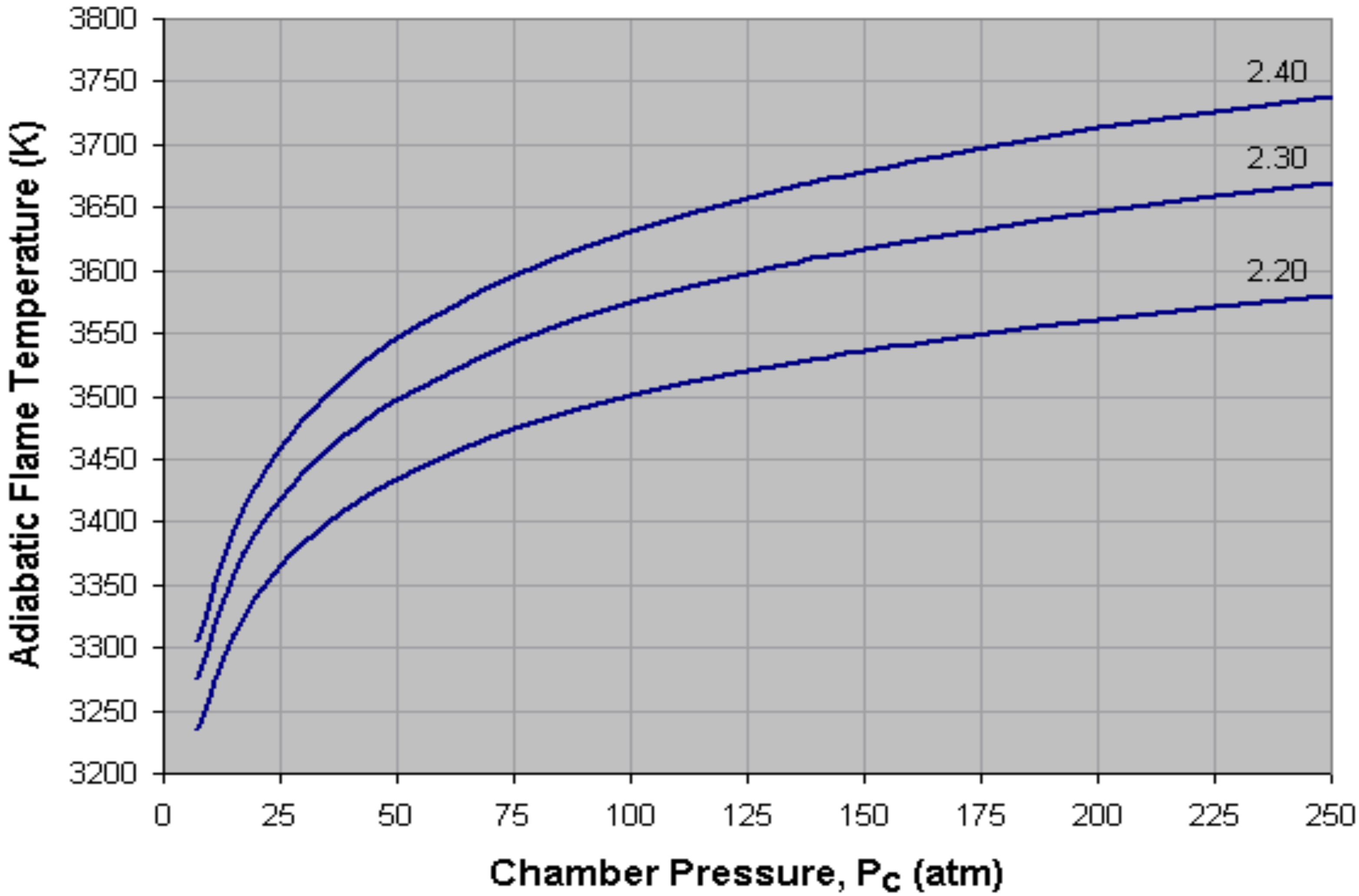
$$Use \rightarrow \left(I_{sp}\right)_{eff} = \frac{2}{3}\left(I_{sp}\right)_{\substack{R2-27A\\initial\\(16.31km)}} + \frac{1}{3}\left(I_{sp}\right)_{\substack{R2-27A\\final\\(105.52km)}}$$

... v) Re-work delta II Homework problem (MAE 5540) using new mean $I_{sp's}$ for stage "1a" and "1b"with the RS-27A aerospike nozzle… compare to earlier results using standard conical nozzle for stage 1

assume conventional nozzles for Both Gem-40 and AJ10-118 Second Stage Engine

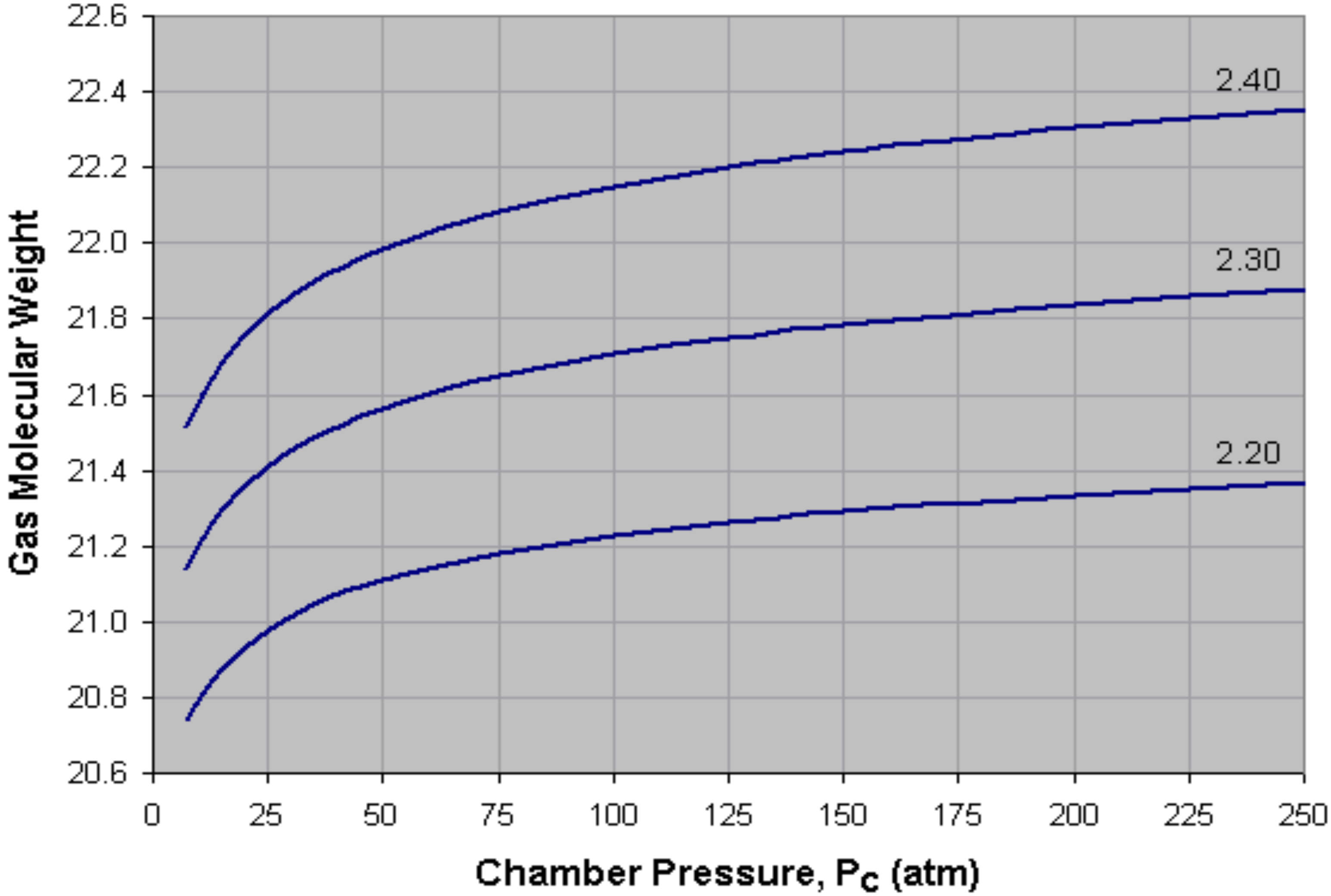
Homework 3 (cont'd)

Lox/Kerosene



Homework 3 (cont'd)

Lox/Kerosene

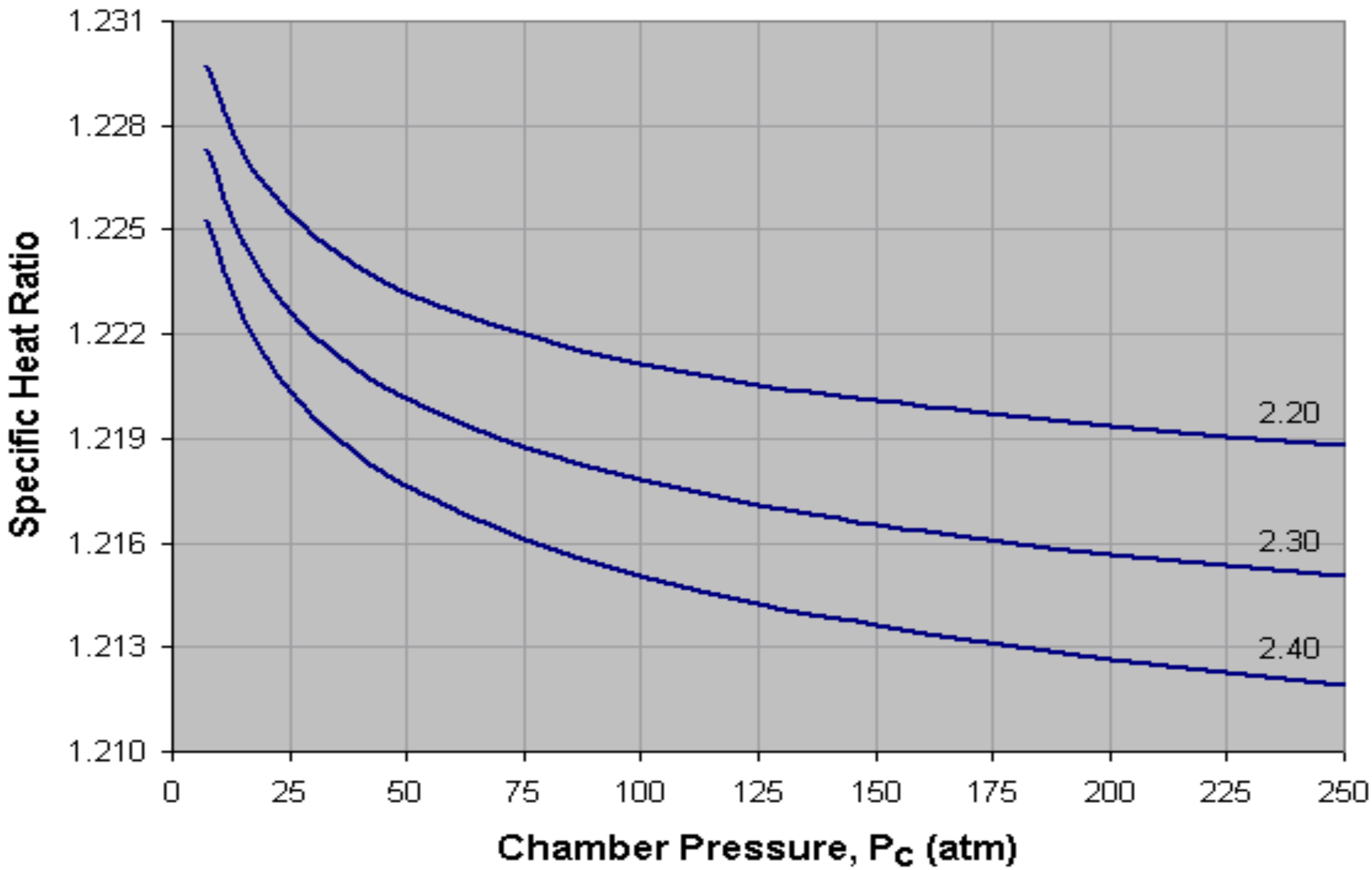


UtahState UNIVERSITY

Mechanical & Aerospace Engineering

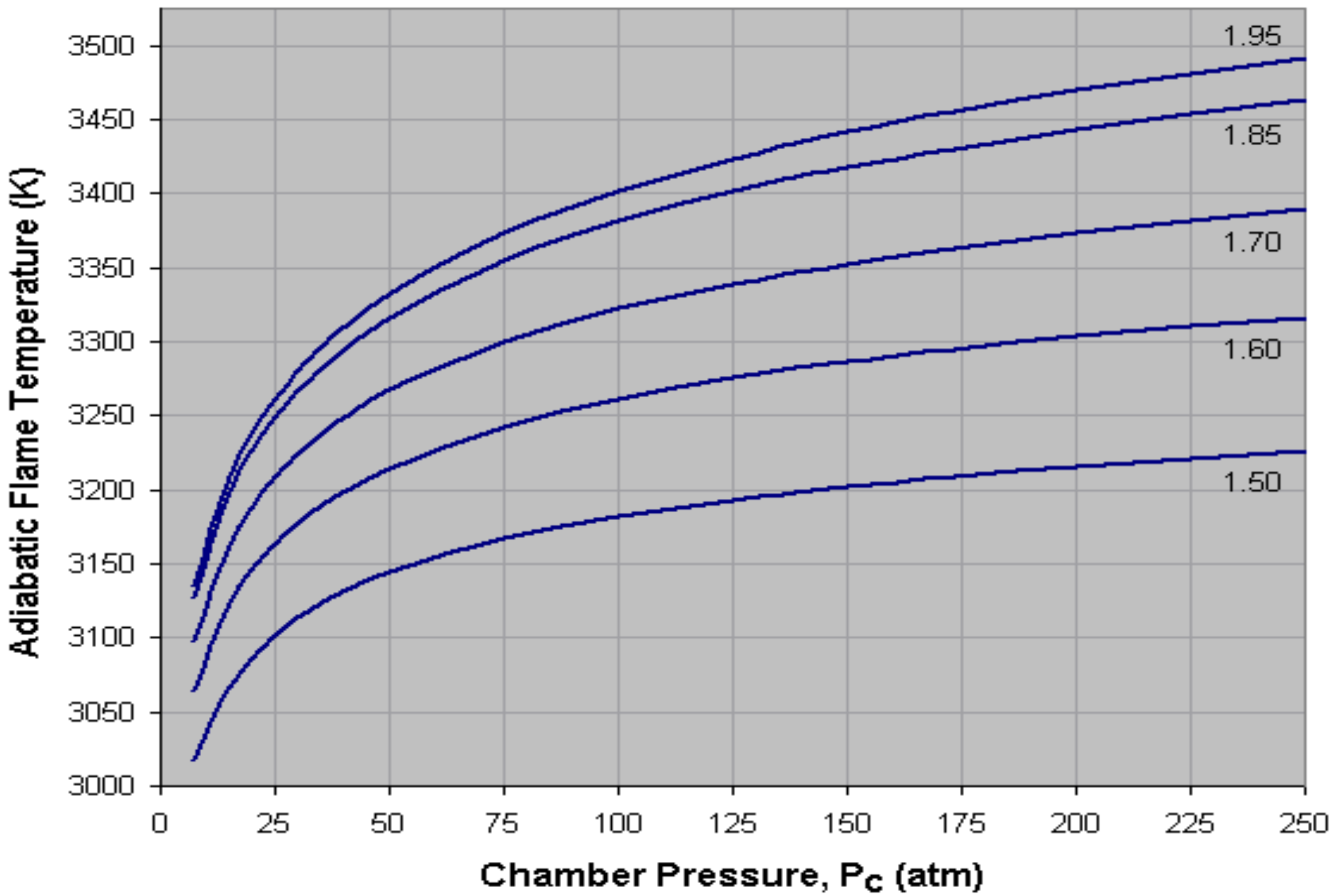
Homework 3 (cont'd)

Lox/Kerosene



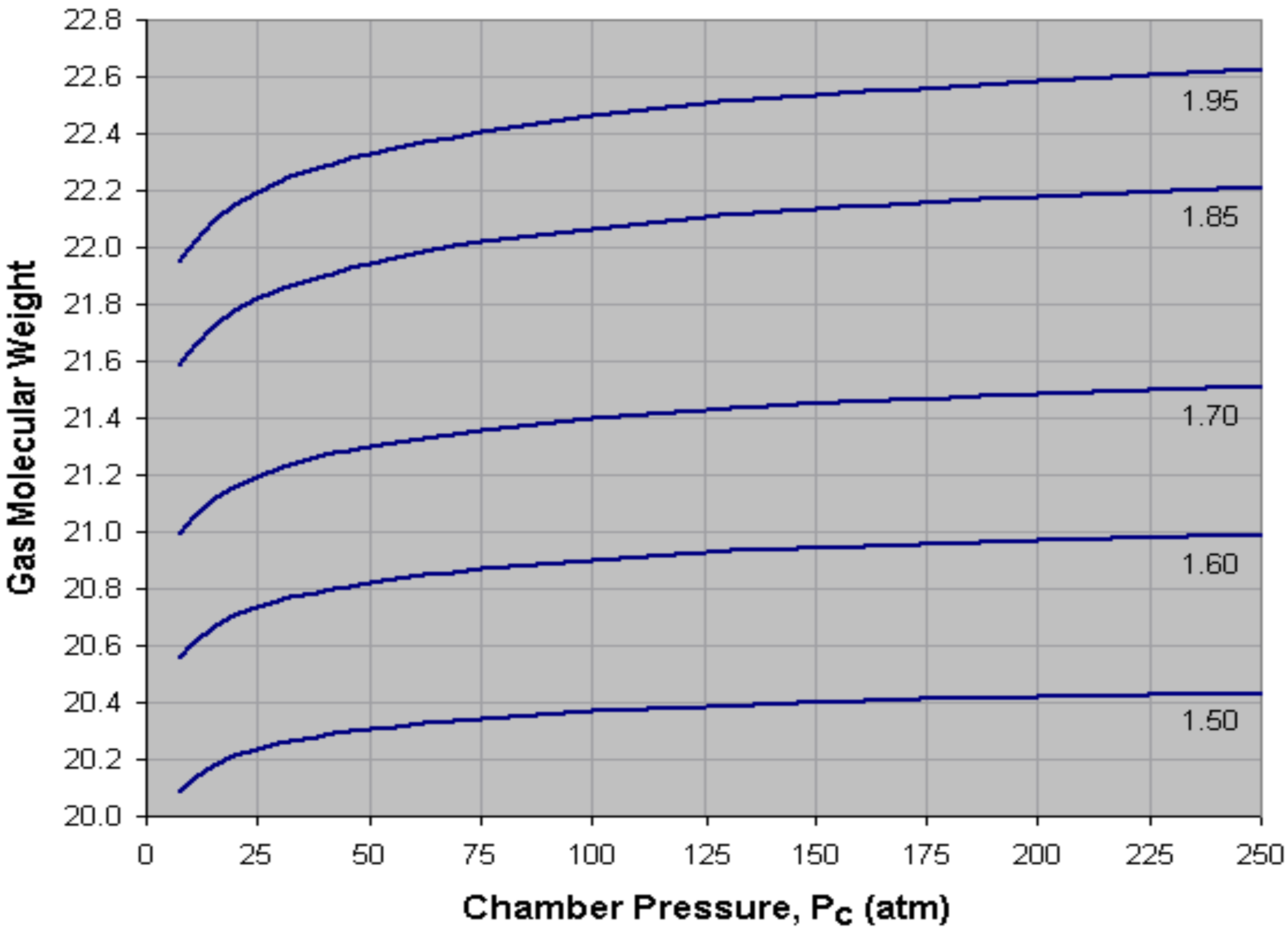
Homework 3 (cont'd)

N_2O_4/Aerozine 50



Homework 3 (cont'd)

N_2O_4/Aerozine 50



Homework 3 (cont'd)

N_2O_4/Aerozine 50