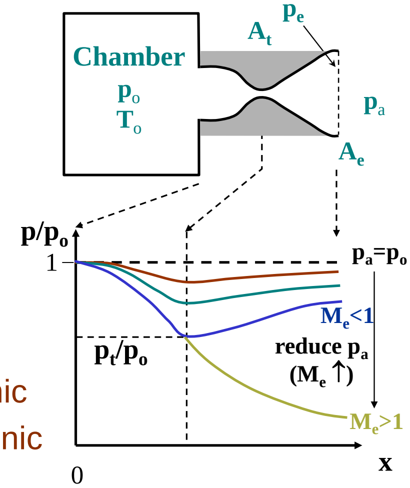
Rocket Propulsion Basics

Under- and Over-Expanded Nozzles

Seitzman Ideal Nozzles-16
Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Expansion in CD Nozzles

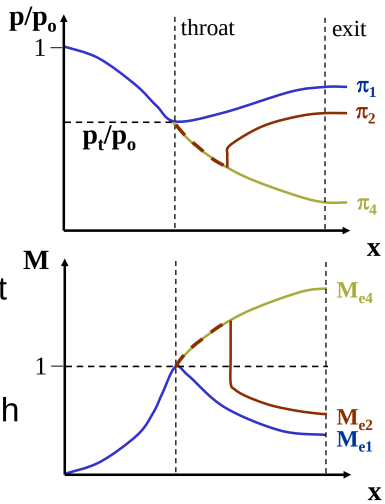
- As ambient (back) pressure is reduced (or p_o increased), flow increases
- Once p_a/p_o low enough to get sonic flow at throat:
  2 ***isentropic*** solutions
  - higher $p_a(=p_e)$, subsonic
  - lower $p_a(=p_e)$, supersonic



Seitzman Ideal Nozzles-17
Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Nonisentropic Solutions

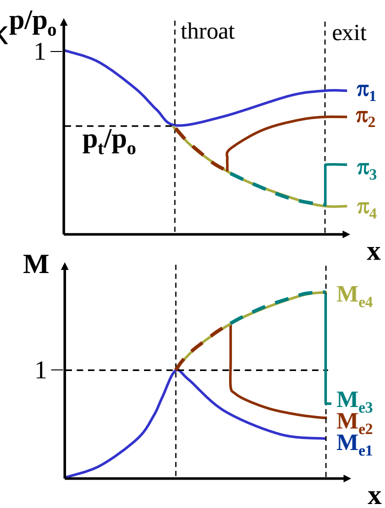
- What happens for p_a/p_o in between the isentropic solutions?
  - nonisentropic flow
- For $p_a/p_o<(p_a/p_o)_1\equiv\pi_1$
  - flow starts to go supersonic after throat
- For $\pi_1>\pi>\pi_4$, p must increase above super-sonic isen. case to match $p_a \Rightarrow$ shock in diverging section



Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Shocks Inside Nozzle

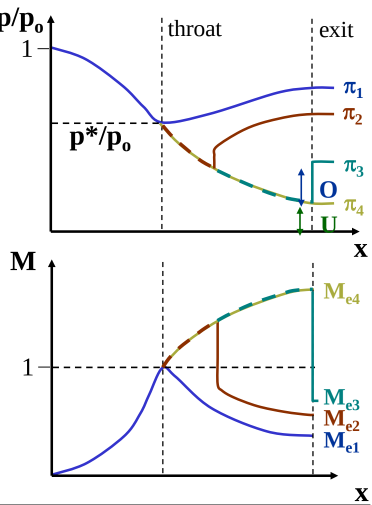
- Over what range of back pressures will there be shock in nozzle
  - until shock occurs at exit plane of nozzle
- So, question becomes - what is exit pressure when normal shock sits at exit?
  - **combine isentropic flow with shock to match $p_e=p_a$**



Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Over- and Underexpanded Nozzles

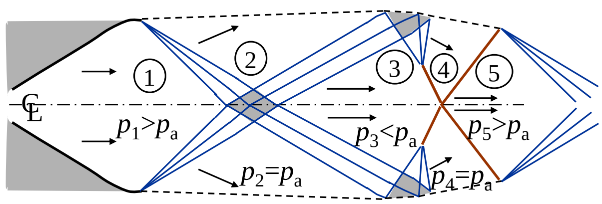
- What happens if p_a/p_o goes below value where shock is at exit, $<\pi_3$
  - isentropic flow up to exit, **supersonic exhaust**
  - shocks (and expansions) **outside nozzle** (not normal shocks)
- $\pi_4<\pi<\pi_3$: **Overexpanded**
- $\pi<\pi_4$: **Underexpanded**
- Generally, rocket nozzles over- or underexpanded*



*except during startup/shutdown

Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

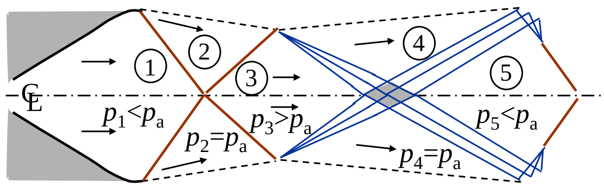
Underexpanded Nozzle Exhaust



- For $p_e>p_a$, nozzle produces a jet flow consisting of regions of *decreasing* and *increasing* p (or density)
  - inviscid flow (ideal), process would continue endlessly
  - viscous case (real), viscous losses and turbulent mixing with surroundings causes wave pattern to decay after small number of cycles

Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Overexpanded Nozzle Exhaust

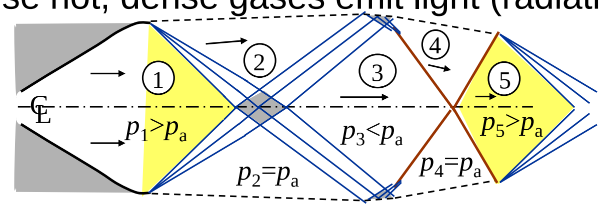


- For $p_e < p_a$, nozzle produces jet flow consisting of regions of *increasing* and *decreasing* pressure (or density)
  - same pattern as for underexpanded case, just “out-of-phase” (compressions first, then expansions for overexpanded vs. expansions then compressions for underexpanded)

Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Mach (Shock) Diamonds

- Regions of high pressure, also have high density (and temperature)
  - these hot, dense gases emit light (radiation)



SR-71 at takeoff

Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved

Georgia Tech College of Engineering

Altitude Variation in Exhaust Plume

- Which is high altitude test?

Credit: NASA

Credit: AEDC

Copyright © 2012, 2017, 2018 by Jerry M. Seitzman. All rights reserved