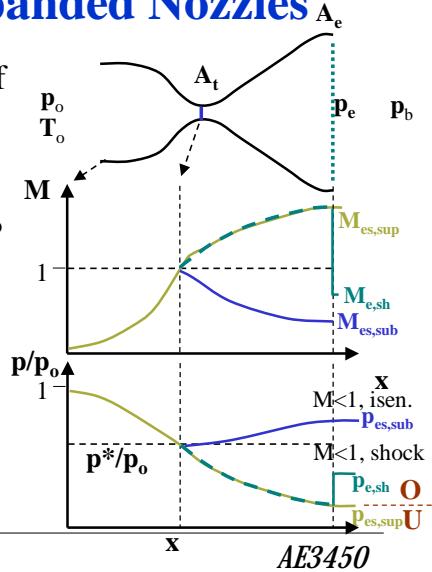


Under/Overexpanded Nozzles

- Recall previous analysis of CD nozzles, e.g., as back pressure is reduced
- Have looked at range of p_b that produce
 - *isentropic* solutions or
 - *shocks in nozzle*
- What happens when
 - $p_b < p_{es,sup}$ (U)
 - $p_{es,sup} < p_b < p_{e,sh}$ (O)



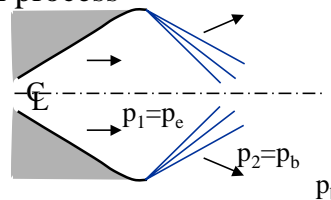
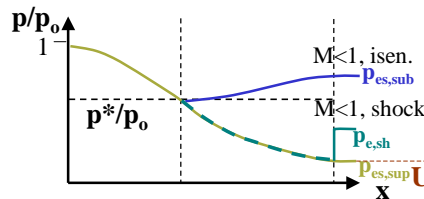
Under/Overexpanded Nozzles - 1

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Underexpanded Nozzles

- Start with $p_b < p_{es,sup}$
 - **underexpanded case**
 - $p_e > p_b$ (not enough expansion has occurred)
- So **boundary condition** at exit requires a supersonic expansion process
 - ⇒ (2-d) Prandtl-Meyer flow
 - flow turns, pressure drops to back pressure
 - but flow must not cross centerline (symmetry line; like a wall)



Under/Overexpanded Nozzles - 2

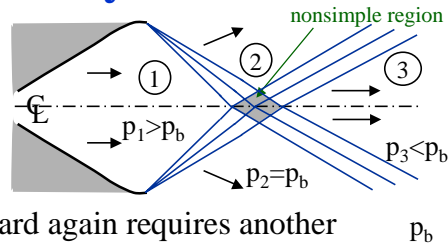
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Centerline Boundary Condition

- Centerline

- flow along centerline must be parallel to centerline



- to get flow to turn inward again requires another PM expansion
- but second expansion means pressure in region 3 drops below back pressure ($p_3 < p_2 = p_b$)
- so now we will need to do something to match our pressure boundary condition at the edge of the jet

Under/Overexpanded Nozzles - 3

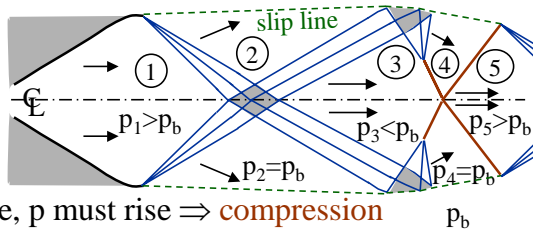
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Jet Boundary Condition

- Jet boundary

- along “edge” of jet must satisfy pressure b.c.



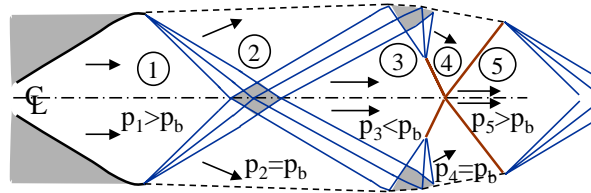
- to match pressure, p must rise \Rightarrow compression
- can get PM compression waves
- combine to form oblique shocks, turn flow inward
- centerline (velocity) boundary condition requires reflected compression waves
- now pressure exceeds surrounding pressure ($p_5 > p_b$), way we started, so process/cycle repeats itself

Under/Overexpanded Nozzles - 4

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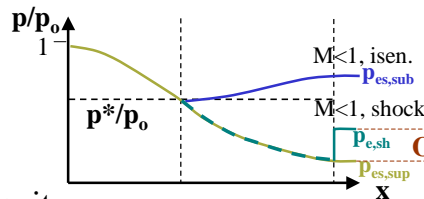
Underexpanded Jet



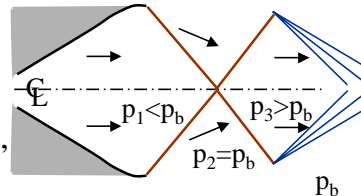
- For $p_e > p_b$, nozzle produces a jet flow consisting of regions of *decreasing* and *increasing* p (or density)
 - inviscid flow (ideal), process would continue endlessly
 - viscous case (real), viscous losses and turbulent mixing with surroundings causes wave pattern to decay after small number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

Overexpanded Nozzles

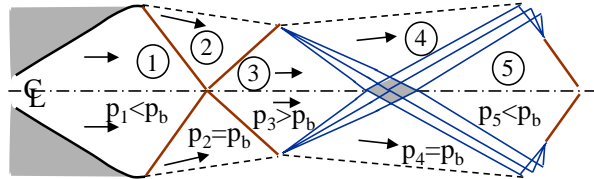
- $p_{e,sup} > p_b > p_{e,sh}$
 - **overexpanded case**
 - too much expansion has occurred



- So **boundary condition** at exit requires a supersonic compression process
 - ⇒ oblique shock (2-d)
 - flow turns, pressure rises to back pressure
 - flow must not cross centerline, so get reflected shocks
 - then expansion to match p , etc.



Overexpanded Jet



- For $p_e < p_b$, 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)

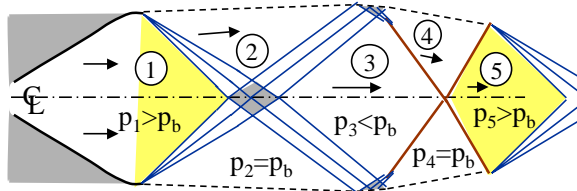
Under/Overexpanded Nozzles - 7

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Mach (Shock) Diamonds

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



SR-71
at
takeoff

Under/Overexpanded Nozzles - 8

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