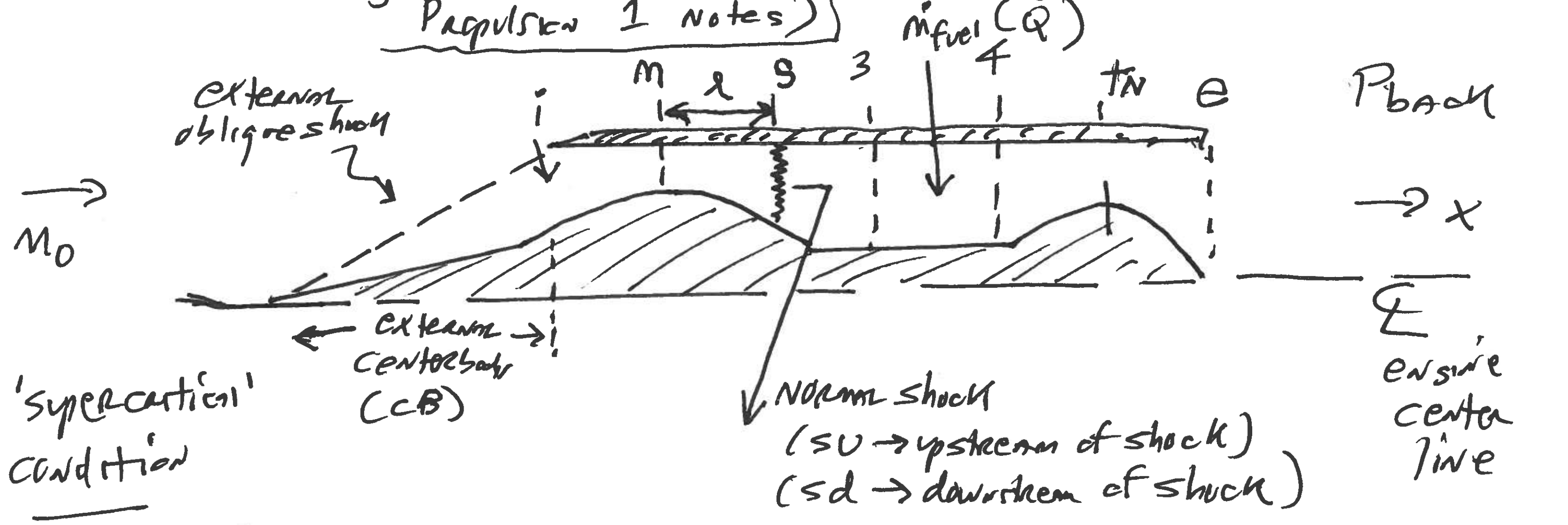
Ramjet Operability → throttling and control of engine / inlet unstart

Schematic of the 'started' ramjet engine with fixed geometry (Kantrowitz-Donaldson type of inlet: see Propulsion 1 notes)



'supercritical' condition

m = inlet physical throat location (this is a physical throat, Not an aerodynamic throat, i.e. $M_m > 1.0$;

i.e., $\frac{A_i}{A_m} < \left(\frac{A_i}{A^*}\right)_{isentropic}$ (supersonic locus)

i.e., A_m is $> A^*_{isentropic\ reference}$!

s = shock location; downstream of m

l = axial distance between m and s (called shock margin)

3 → 4 burner

tN = nozzle throat, $M_{tN} = 1.0$ (This implies P_{back} in comparison to P_{t4} is sufficiently low to pull Mach to 1 at tN ...)

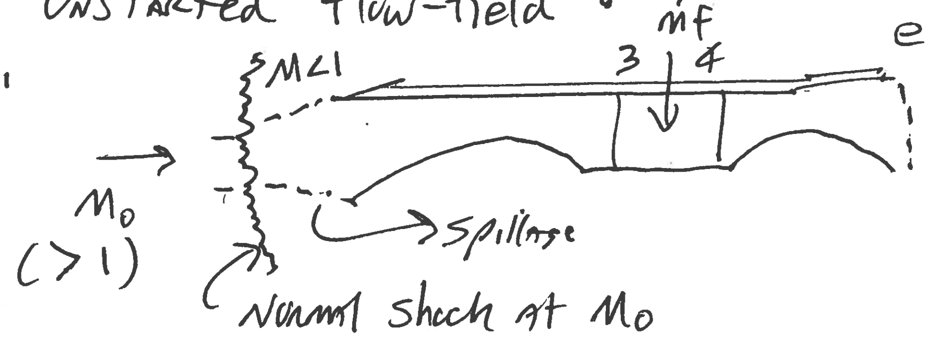
For following discussion, we will assume no external CB so $M_i = M_0$ and isentropic flow except thru shock and burner ...

Stable ramjet operation at supersonic flight Mach requires the avoidance of inlet/engine unstart.

[Unstart is characterized by a strong normal shock forward of the inlet face, with large P_t losses, mass spillage, and resulting degradation in performance.

Unstarted flow-field:

'subcritical' condition



Thrust ~ $\dot{m}_{air}$ ingested!

& lower P_t → lower thrust

Stable operation at cruise (engine started) requires that a weak normal shock be maintained just downstream of the inlet throat (m) with shock margin ('ℓ') as small as practical in order to minimize the P_t losses thru the shock. Obviously, the smaller the shock margin, the weaker the shock...

Fact: Shock at m is 'neutrally stable', i.e., if it moves even marginally forward (into the upstream converging part of inlet), it is unstable and will travel upstream of inlet face (station i), resulting in unstarted flow-field as shown...
This situation (either moment of starting or unstarting) is 'critical' (known as 'critical operation')

Fact: Even with shock downstream of m, changes in M_i (say due to changes in α, gusts, etc.) with either constant throttle or during accel/decel can cause the shock to move rapidly forward to m, then unstart ...

[So, in general, shock needs to be 'maintained' between m and 3 for stable started operation. If M_i is fixed and the engine is throttled (i.e., $\dot{m}_{fuel}$ changed), the shock location, i.e. ℓ, will change (we will show this).

[We will assume that $A(x)$ thru engine is known (hence, if A_s known → ℓ, shock margin, known)
(ℓ is a function of x)

[How can we analyze this ramjet flow-field]
(for fixed geometry) ??

[We are interested in predicting the shock margin (ℓ) and the associated A_s for a given $\dot{m}_{fuel}$.

[However, to set the problem up, assume A_s known (hence ℓ known → shock is 'located' in inlet) and then calculate the $\dot{m}_{fuel}$ required for that situation ...

→ With this, this means all conditions at station 3 (combustor entrance) can be found, including M_3 (just use isentropic relations and normal shock relations)

Also, since geometry is fixed & we have

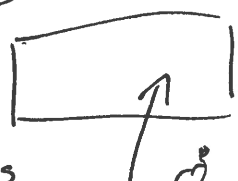
$M_{tN} = 1.0$ (i.e. $A_{tN} = A^*_{\text{actual nozzle}}$) ...

then M_4 is fixed as well (based on known A_4 / A_{tN} & isentropic flow (subsonic) from 4 to tN)

So, by assuming an A_S (or equivalently a 'ℓ') we know both M_3 & M_4 (& all conditions at 3!)

3 4

All conditions at 3 known, including M_3 →



→ M_4 known

$\dot{Q}$? → what is $\dot{Q}$?

$(\dot{Q} = \dot{m}_f h)$ heating value of fuel

This then determines (uniquely) a $\underline{\underline{\dot{Q}_{3\to 4}}}$ required (the $\dot{Q}$ that will give the M_4) by doing a Rayleigh analysis ...

So, for instance, for Rayleigh flow ($A_4 = A_3$) (& inviscid), a known M_3, T_{t3}, M_4 gives $q_{3\to 4}$, i.e. $\dot{Q}_{3\to 4}$ (since $\dot{m}$ known)

Hence $\dot{Q}$ (heat rate) or $\dot{m}_{fuel}$ (throttling rate) determined by shock margin ℓ in the inlet!

[More usefully, this means that $\dot{q}_{3\to4}$ (or $\dot{m}_{fuel}$) drives the shock margin ℓ (and associated A_s)

[& since A_s must be between A_m & A_3 for started operation, find minimum & maximum throttling limits for ramjet started operation

If this is done, shock moves upstream toward throat (m) as the engine is throttled up (as $\dot{m}_{fuel}$ increases). At maximum throttle point, $\dot{m}_{f_{maximum}}$, the shock stands at m; above this for $\dot{m}_{fuel} > \dot{m}_{f_{max}}$, engine will unstart.

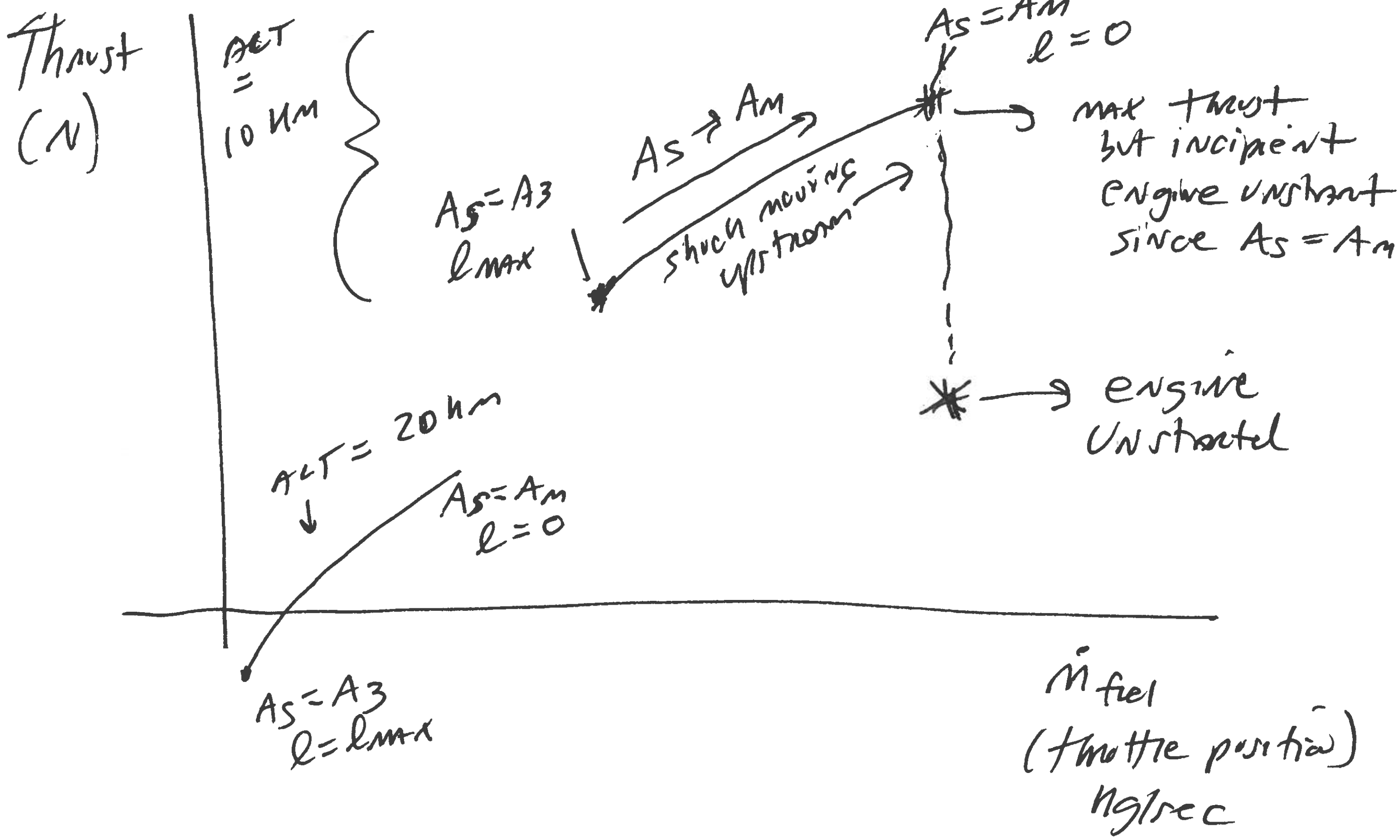
for started (supercritical) flow

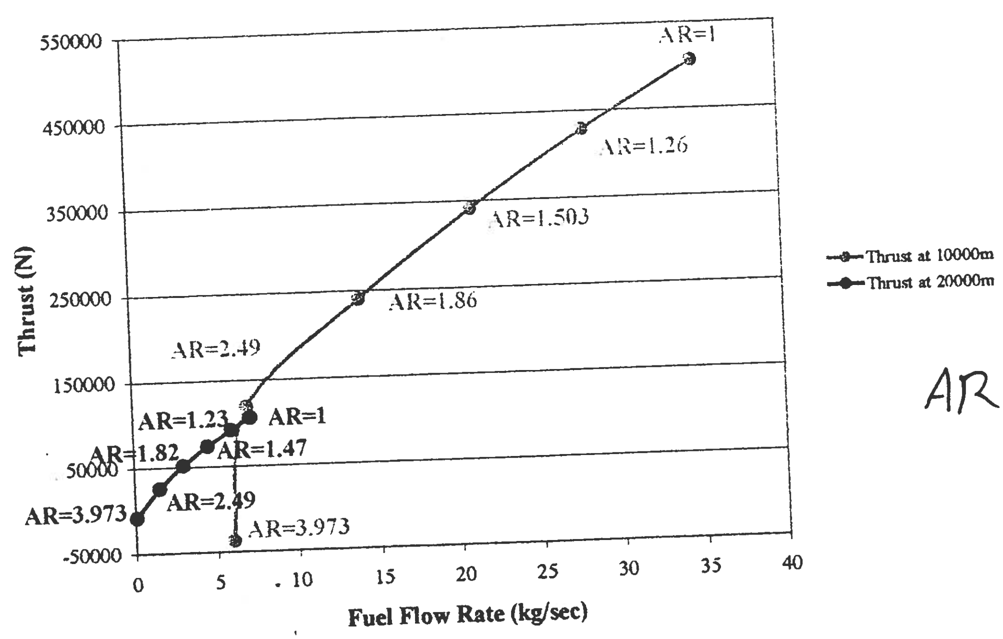
[At $A_s = A_3$ → minimum throttle point
($\ell = \ell_{max}$ → max practical shock margin)

at $A_s = A_m$ ($\ell = 0$) maximum throttle setting
↳ zero shock margin

[This should make sense to you, since for shock at m, subsonic (expanding area) between m and 3, means M_3 will be lowest, hence more fuel can be added between 3 and 4 (recall M_4 fixed)..

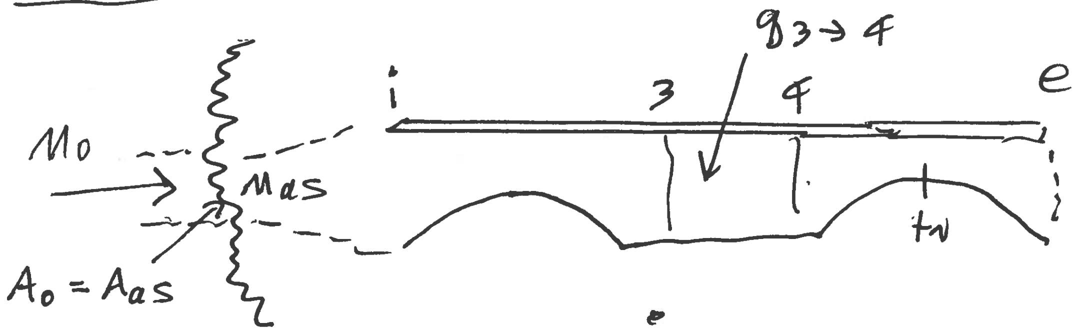
Sketch of resulting performance At $M_0 = 3$ (what you get → sketched):





$$AR = \frac{A_S}{A_M}$$

Analysis of 'Unstarted' engine: (look at where $\dot{m}_f$ same as max $\dot{m}_f$ started) → i.e. looking at 'moment of starting' or 'moment of unstarting'



Realize $q_{3\to4} = \dfrac{\dot{Q}_{3\to4}}{\dot{m}_{air}}$ but $\dot{Q}$ stays same

$\dot{Q} = \dot{m}_{fuel}\, h$ ← heating value of fuel

But $\dot{m}_{air}$ will drop due to spillage (since upstream of i is subsonic) so

$$q_{3\to4}\Big)_{unstarted} > q_{3\to4}\Big)_{started}$$

same $\dot{m}_{fuel}$ ($\dot{m}_{fuel}$ max started)

So since M_4 still fixed (based on $M_{tN} = 1.0$ & known A_4/A_{tN}), $M_3\Big)_{unstart}$ must be less than $M_3\Big)_{started}$ → & can compute $M_3\Big)_{unstart}$ ..

Then since M_{as} known (M_0, normal shock relation)

→ you have known M_{as}, known M_3 & known A_3 ... find A_{as} ($= A_0$) just using isentropic subsonic flow ...

then $\dot{m}_{air} = \rho_0 U_0 A_0$!! → find thrust unstarted!