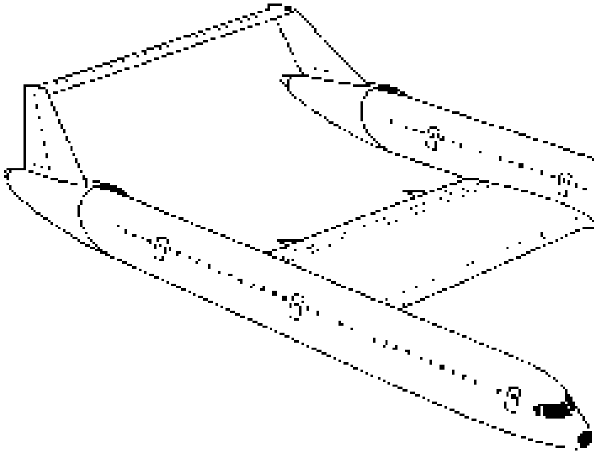
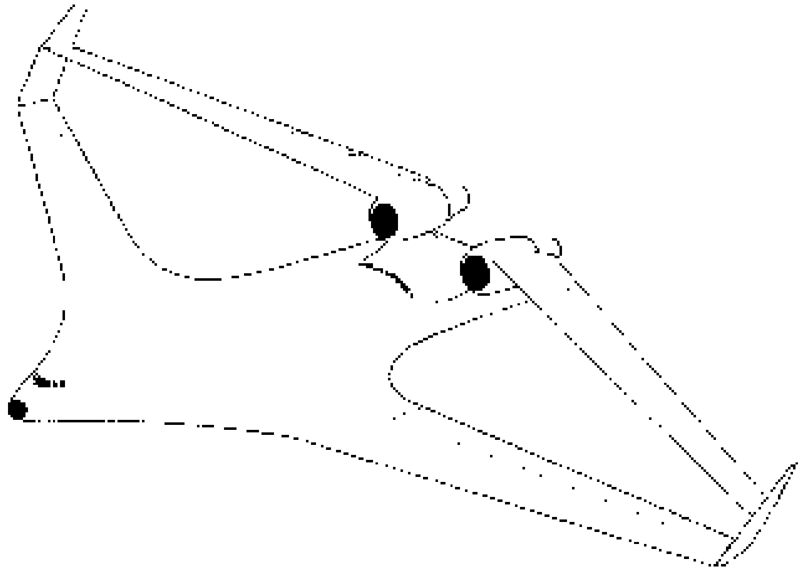
Classical Aircraft Sizing II

W. H. Mason





Advanced Concepts from NASA TM-1998-207644

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Previously (Sizing I)

- Mission definition
- Basic Sizing to Estimate TOGW
- Examples

Now: More Details and Picking *W/S* and *T/W*

- Federal Air Regulations (**FAR**s) and MIL STD Requirements
- Basic Considerations for Wing Size
- Sizing Theory: Getting a Little More Precise
- Tradeoffs, Parametric Studies and **Carpet Plots**

But 1st!

The Conceptual Design Team : *A Suggested Organization*

1. Leader (the keeper of the notebook)
2. Configuration Designer
3. Weights (rock eater) also balance/inertia
4. Vehicle Performance and Mission Analysis
5. Aero Configuration (drag buster)
6. Flight Controls (mechanical as well as handling qualities)
7. Propulsion & Propulsion System Integration
8. Structures/Materials
9. Aircraft Systems
10. Cost and Manufacturing—*last but not least!*

FAR and MIL STD Requirements

Gov't requirements dictate some of the design requirements
- interest is safety, not economic performance
- examples:
  - engine out minimum performance,
    - » *the second segment climb requirement*
  - reserve fuel requirements
  - emergency exits on transport aircraft
  - deicing procedures
- Raymer, App. F
- Roskam: Part VII is entirely devoted to stability and control and performance FAR and MIL requirements
- Key parts for us: Pt 25 (Transport Airplanes), Pt 36 (Noise), Pt 121 (Operations)
- See web charts for definitions for classifying a/c

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see the class web page for a link to the FARs

Takeoff Requirements

Item	MIL-C5011A	FAR Part 23	FAR Part 25
Velocity	$V_{TO} \geq 1.1\ V_S$ $V_{CL} \geq 1.2\ V_S$	$V_{TO} \geq 1.1\ V_S$ $V_{CL} \geq 1.1\ V_S$	$V_{TO} \geq 1.1\ V_S$ $V_{CL} \geq 1.2\ V_S$
Climb Gradient	Gear up: 500 fpm @SL	Gear up: 300 fpm @SL (AEO)	Gear down: 1/2% @ V_{TO} (AEO)
Gear up:	100 fpm @ SL (OEI)		3% @ V_{CL} (OEI)
Field-length definition	Takeoff distance over 50-ft obstacle	Takeoff distance over 50-ft obstacle	115% of takeoff distance with AEO over 35 ft *or* balanced field length*
Rolling coefficient	$\mu = 0.025$	not specified	not specified

* see discussion on next slide

AEO: all engines operating, OEI: one engine inoperative

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from Nicolai, *Fundamentals of Aircraft Design*, , 1975
See Raymer, App. F,

Balanced Field Length (Takeoff)
(Critical Field Length for Military Aircraft)

Following engine failure, at decision speed V_1 ($1.1V_{Stall}$) either:

a) continue takeoff (including obstacle clearance)

or

b) stop

if $V > V_1$ - takeoff

if $V < V_1$ - stop

- V_1 chosen such that distance for both is equal
- details require precise takeoff speed definitions:
  see Sean Lynn's Report, "Aircraft Takeoff Analysis in the Preliminary Design Phase," on our web page or the FARs
- assume smooth, hard, dry runway
- for early design studies this is usually determined without allowing for a stopway past end of runway

2nd Segment Climb Requirement

at V_2, from 35ft to 400 ft above ground level:
for engine failure, flaps in takeoff position, landing gear retracted:

# of engines	climb gradient (CGR)
4	3.0%
3	2.7%
2	2.4%

V_2: airspeed obtained at the 35ft height point

$V_2 > 1.2V_{stall}$ in TO Config or $V_2 > 1.1V_{mc}$

V_{mc} is minimum control speed in the engine out condition

see FAR Part 25 for more complete requirements
or Raymer, App. F

CTOL Landing Requirements

Item	MIL-C5011A (Military)	FAR Part 23 (Civil)	FAR Part 25 (Commercial)
Velocity	$V_A > 1.2\ V_S$ $V_{TD} > 1.1\ V_S$	$V_A > 1.3\ V_S$ $V_{TD} > 1.15\ V_S$	$V_A > 1.3\ V_S$ $V_{TD} > 1.15\ V_S$
Field-length definition	Landing Distance over 50-ft obstacle	Landing Distance over 50-ft obstacle	Landing Distance over 50-ft obstacle divided by 0.6
Braking coefficient	$\mu = 0.30$	not specified	not specified

from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975
see Raymer, App. F,

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Missed Approach Requirement

One engine out at landing weight,
- in the approach configuration and landing gear retracted

# of engines	climb gradient (CGR)
4	2.7%
3	2.4%
2	2.1%

see FAR Part 25 for more complete requirements
[also Raymer, App. F,

Reserve Fuel Requirements

- FAR Part 121 and ATA standards (more stringent than Pt 121)

Domestic Operations

- fly 1 hr at end of cruise fuel flow for 99% max range
- execute missed approach, climb out and fly to alternate airport 200nm away

International Operations

- fly 10% of trip time at normal cruise altitude at fuel flow for 99% max range
- execute a missed approach, climbout and fly to alternate airport 200nm away

Flight to Alternate Airport

- cruise thrust for 99% max range, then hold at greater of max endurance or min speed for comfortable handling
- cruise at BCA unless greater than climb/descent distance

Approximation often used in very early stages of design studies:

- add 400 to 600 nm to design range

Stability and Control

- FAR requirements are qualitative only
- MIL STD 1797A (was MIL SPEC 8785) is used to establish quantitative guidelines for control power requirements and handling qualities
- Good flying qualities depend on good nonlinear aerodynamics (stall characteristics):
  - in early design, before wind tunnel and flight test, draw on lessons from the past (Stinton's *Flying Qualities* book is one good place to start)
  - expect a lot of effort to go into getting this right

Basic Considerations for Wing Size

- Wing weight is important
- Integrate Aerodynamics and Structures for minimum weight design
- Wing loading is an important design parameter
  - driven by two opposing requirements
- Can define problem reasonably well

Structural Technology

Represent with weight equations developed from past designs

Wing Weight equation for Fighters (from Nicolai):

$$W_{WNG} = 3.08 K_T \left(\frac{K_{PIV} N W_{TO}}{(t/c)} \left[1 + \tan^2 \Lambda_{c/2} \right]^2 \times 10^{-6} \right)^{.593} \times \left[(1+\lambda) AR \right]^{.89} S_W^{.741}$$

K_T – technology factor

K_{PIV} – variable sweep factor $= 1.175$ (1 for fixed geometry)

W_{TO} – TOGW

N – ultimate load factor ($=$ 11 for fighters, 1.5×7.33)

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+ standard variables - t/c, Λ, λ, AR, S

Regrouping the Weight Equation:

$$W_{WNG} = 3.08 K_T \left(\frac{K_{PIV} N W_{TO}}{(t/c)} \left[1 + \tan^2 \Lambda_{c/2}\right]^2 \times 10^{-6} \right)^{0.593} (1+\lambda)^{0.89} \, b^{1.78} S_W^{-0.149}$$

Drivers:
- thickness, *t/c*
- span, *b*
- sweep, Λ
- Wing area, *S* (different for fixed *AR* or *b*)
- taper, λ
- TOGW (W_{TO})

for low wing weight:
- thick wings (*t/c* large)
- low span (*b* low)
- high taper (λ small)
- low sweep (Λ small)

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Wing Size and Wing Loading Issues
Consider Wing Loading to Find Wing Area

- Specific Range (*sr*), best range formula, drag rise neglected

$$best\ sr = \frac{1.07}{sfc}\left\{\frac{(W/S)}{\rho}\right\}^{1/2}\frac{\{AR\cdot E\}^{1/4}}{\{C_{D_0}\}^{3/4}}\frac{1}{W}$$

Increase: *W/S*, altitude (decreases ρ) , *AR*, *E* (*L/D*)

Decrease: zero lift drag, weight (*W*), *sfc*

Here: HIGH *W/S* is good

Wing Loading Considerations (Cont'd)

Sustained Maneuvering

$$n = \frac{q}{(W/S)}\sqrt{\pi ARE\left(\frac{T}{qS} - C_{D_0}\right)}$$

Takeoff

$$l_t = 37.7 \cdot TOP, \qquad TOP = \frac{(W/S)}{\sigma \cdot C_{L_{\max}}(T/W)}$$

Landing

$$V_{APP} = 17.15\sqrt{\frac{W/S}{\sigma \cdot C_{L_{APP}}}}, \qquad (knots)$$

Here: LOW W/S is good

Sizing Theory: Getting a Little More Precise

- Can use simple representation of technologies and do some decent analysis
- Several possibilities:
  - rubber airplane and engine
  - rubber airplane and specified engine
  - new wing on existing airplane
  - *etc.*

Thrust to Weight and Wing Loading

Engine size (or thrust to weight, T/W)

• based on sizing the engine to meet constraints
typically established by the Specs we've discussed

Wing size (or wing loading, W/S)

• also based on meeting key requirements

T/W - W/S charts are typically used

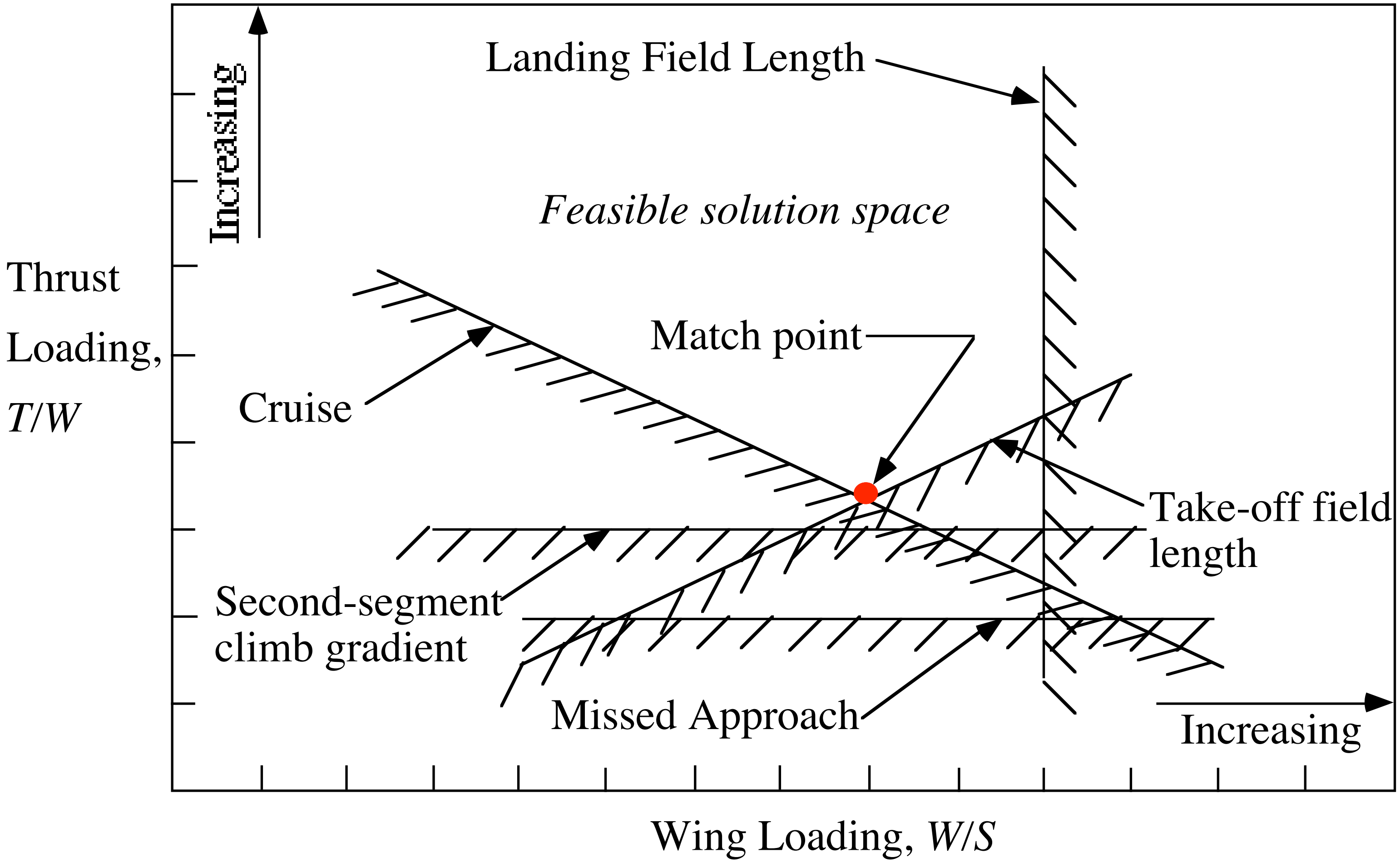
• putting all the constraints on the plot lets
you select the best combination

Often the wing is allowed to be bigger,
- to allow for future growth

Prop Airplanes use Power Loading, *W/P* in place of *T/W*

see L.K. Loftin, Jr., "Subsonic Aircraft: Evolution and the Matching of Size to Performance," NASA RP 1060, Aug. 1980,
- available as a pdf file from http://ntrs.larc.nasa.gov/
(see pages 358-360, for examples for prop airplanes).

Thrust Loading and Wing Loading Matching



from L.K. Loftin, Jr., “Subsonic Aircraft: Evolution and the Matching of Size to Performance,” NASA RP 1060, Aug. 1980

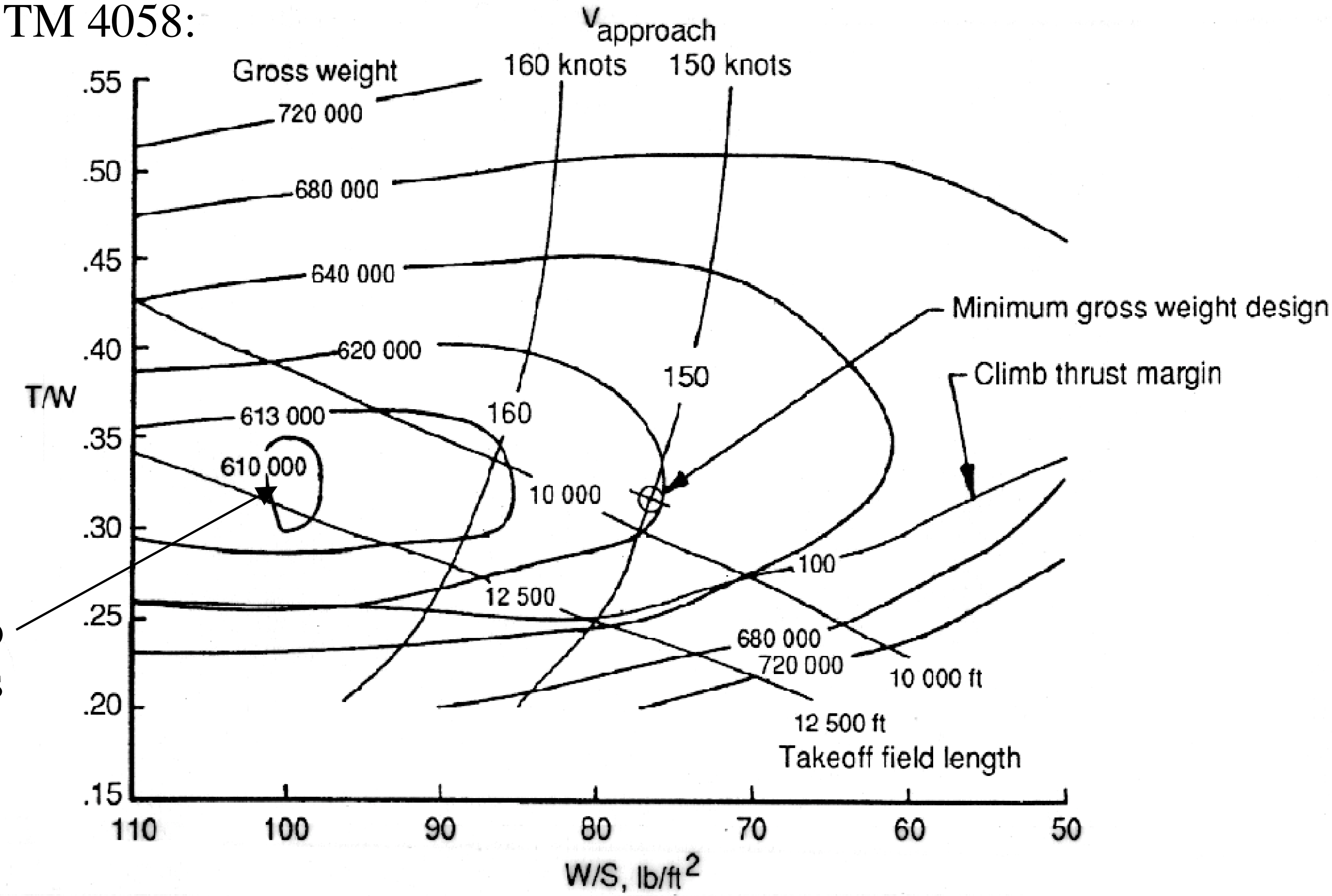
Tradeoffs and Parametric Studies

- Pervasive in design: establish a basis for design decisions
- Graphical representation required, two approaches
  - the Thumbprint plot
  - the Carpet plot
- Need a picture to get insight

Thumbprint Plot for an HSCT

Contours of constant aircraft weight are drawn on the *T/W* - *W/S* chart, which also contains the constraints. The "Best Design" can be picked.

from NASA TM 4058:



Minimum w/o constraints

note decreasing scale for *W/S* in this example

Example of Constraint Lines

(approximate examples, be able to derive your own)

Takeoff: $$T/W) \cong \frac{37.7 \cdot W/S)_{\text{Takeoff}}}{\sigma \cdot C_{L_{\max\text{ TO}}} \cdot s_{TOFL}}$$

Landing: $$W/S) \cong 2.8\rho \cdot C_{L_{\max\text{ Ldg}}} \cdot s_{ldgfl}$$

Cruise ($T = D$):
$$T/W) = q\frac{C_{D_0}}{(W/S)_{cruise}} + \frac{(W/S)_{cruise}}{q\pi ARE}$$

Climb gradient requirements:
$$T/W) = \left(\frac{N}{N-1}\right)\left(CGR + \frac{1}{L/D}\right)$$

where, $\sigma = \rho / \rho_{sea\ level}$

Note: convert T/W to M=0,h=0 values, W/S to takeoff values, N is the number of engines, where we assume one engine out is the critical case, CGR is the climb gradient, q implies best altitude, Mach, and L/D should be for correct flight condition.

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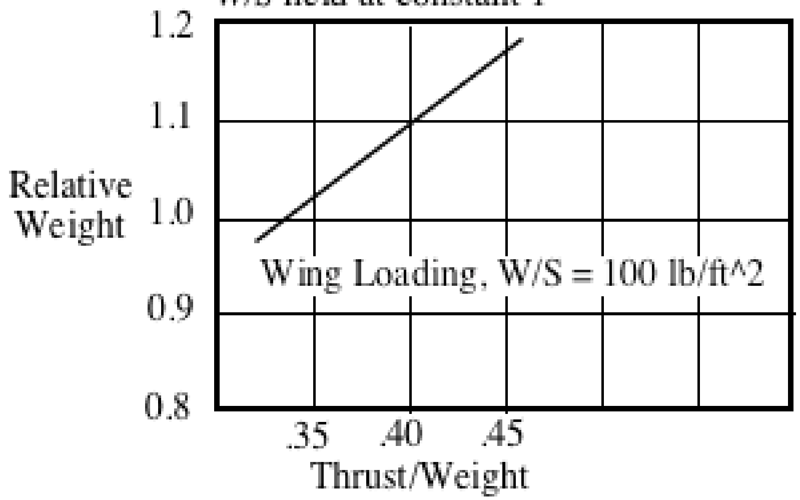
Carpet Plots

- Simple Parametric Plots can be confusing
- Shifting the plot axis provides a better way to understand parametric studies
- Resulting plot is called a carpet plot
- Particularly good for examination of the effects of constraints

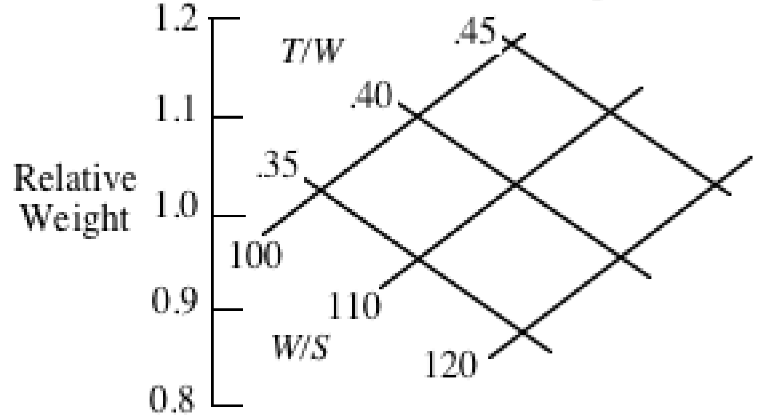
See also the writeup on carpet plots from Sid Powers that is also available with these charts.

How to Construct a Carpet Plot

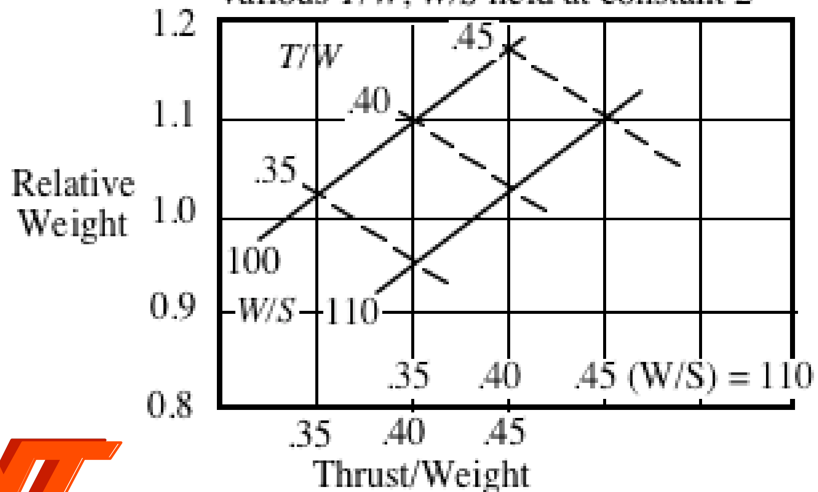
Step 1: plot weights for various *T/W*, *W/S* held at constant 1



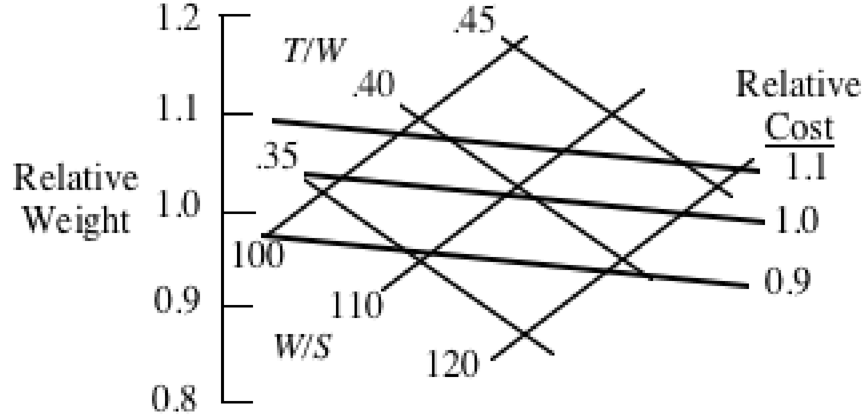
Step 3: complete the baseline carpet, and delete the abscissa and the plot lines



Step 2: shift scale, plot weights for various *T/W*, *W/S* held at constant 2



Step 4: add constraints



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based on Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

An Example Using Carpet Plots

Examine:

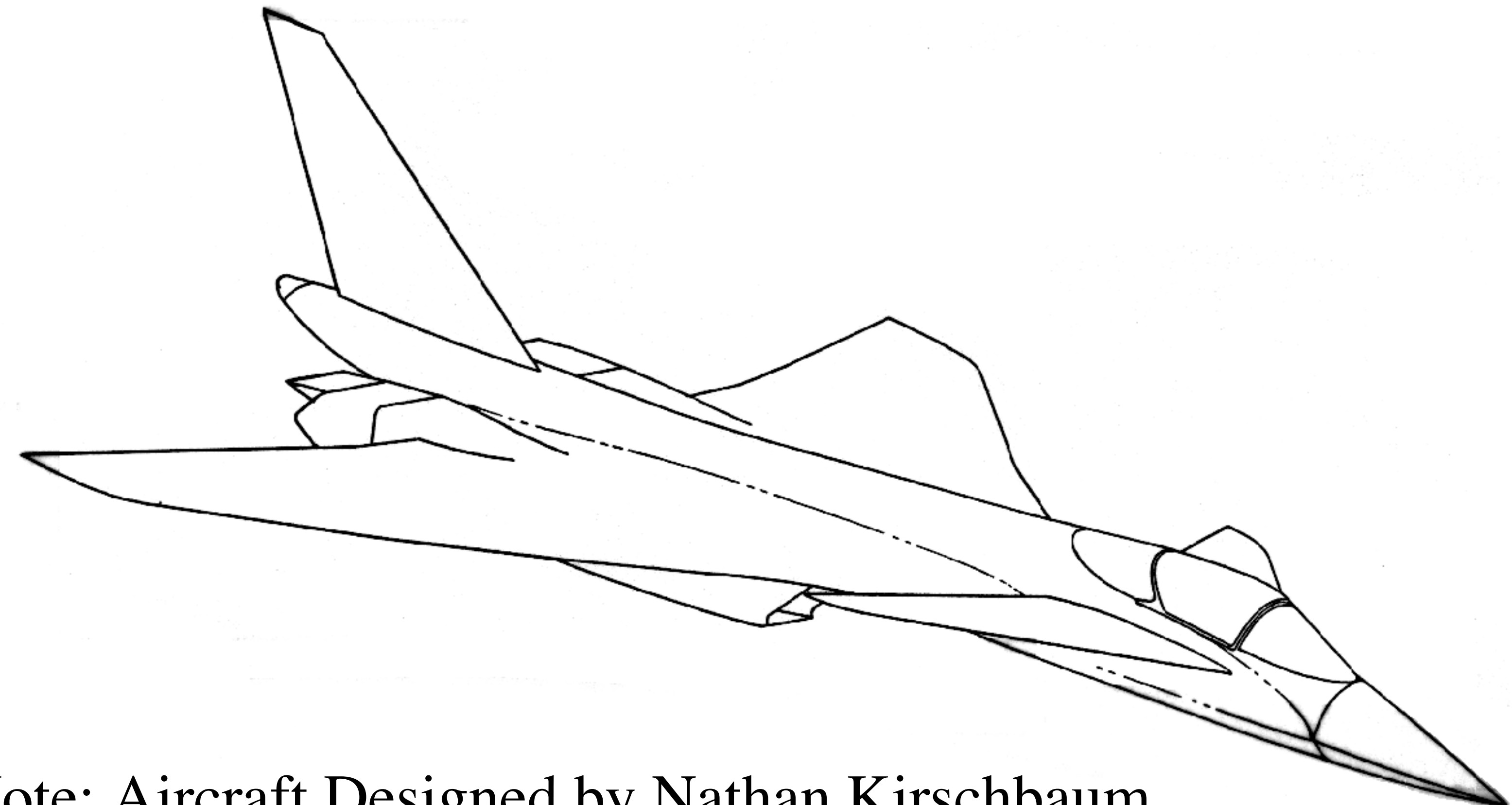
- *W/S* - the Wing Loading
- *T/W* - the Thrust Loading

Understand *W/S* and *T/W* Sensitivity and the impact of constraints:

- Weight to meet mission requirements
- Effect of M0.9, 30K Sustained Maneuver Req't.
- Accel: M0.9 to M1.6 at 30K
- Field Performance (landing and takeoff)
- All constraints included on the same plot

Impact of Improved Maneuvering Technology

The Example Design: A Supersonic Fighter



Note: Aircraft Designed by Nathan Kirschbaum

Source: W.H. Mason, “A Wing Concept for Supersonic Maneuvering,” NASA CR 3763, 1983

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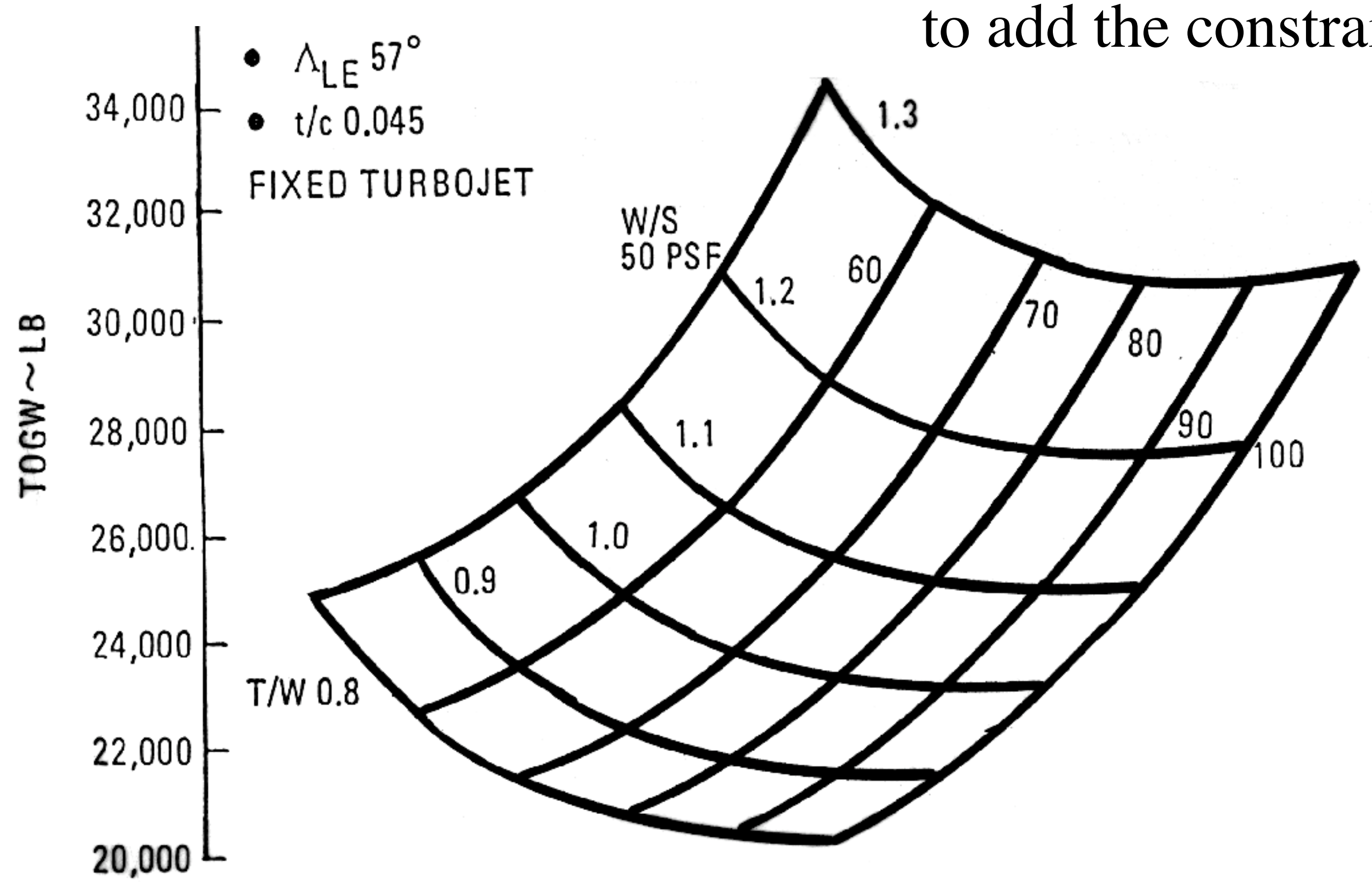
Basic Carpet
(each point is a solution for the given mission)

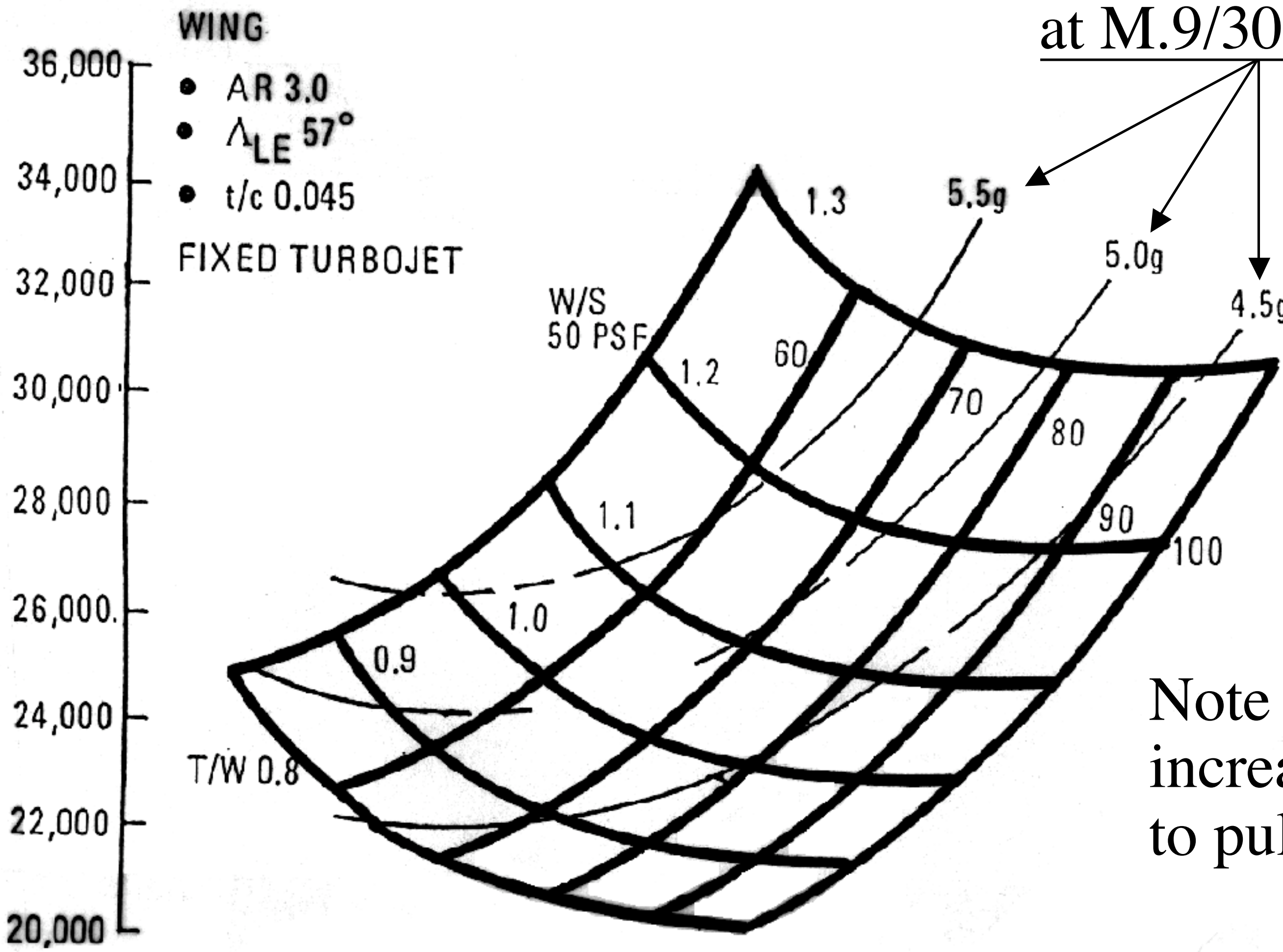
The baseline chart, ready to add the constraints



Carpet with Transonic Maneuver Constraints

Constraints for *g*'s at M.9/30K ft added

TOGW lbs



Note large weight increase required to pull more *g*'s

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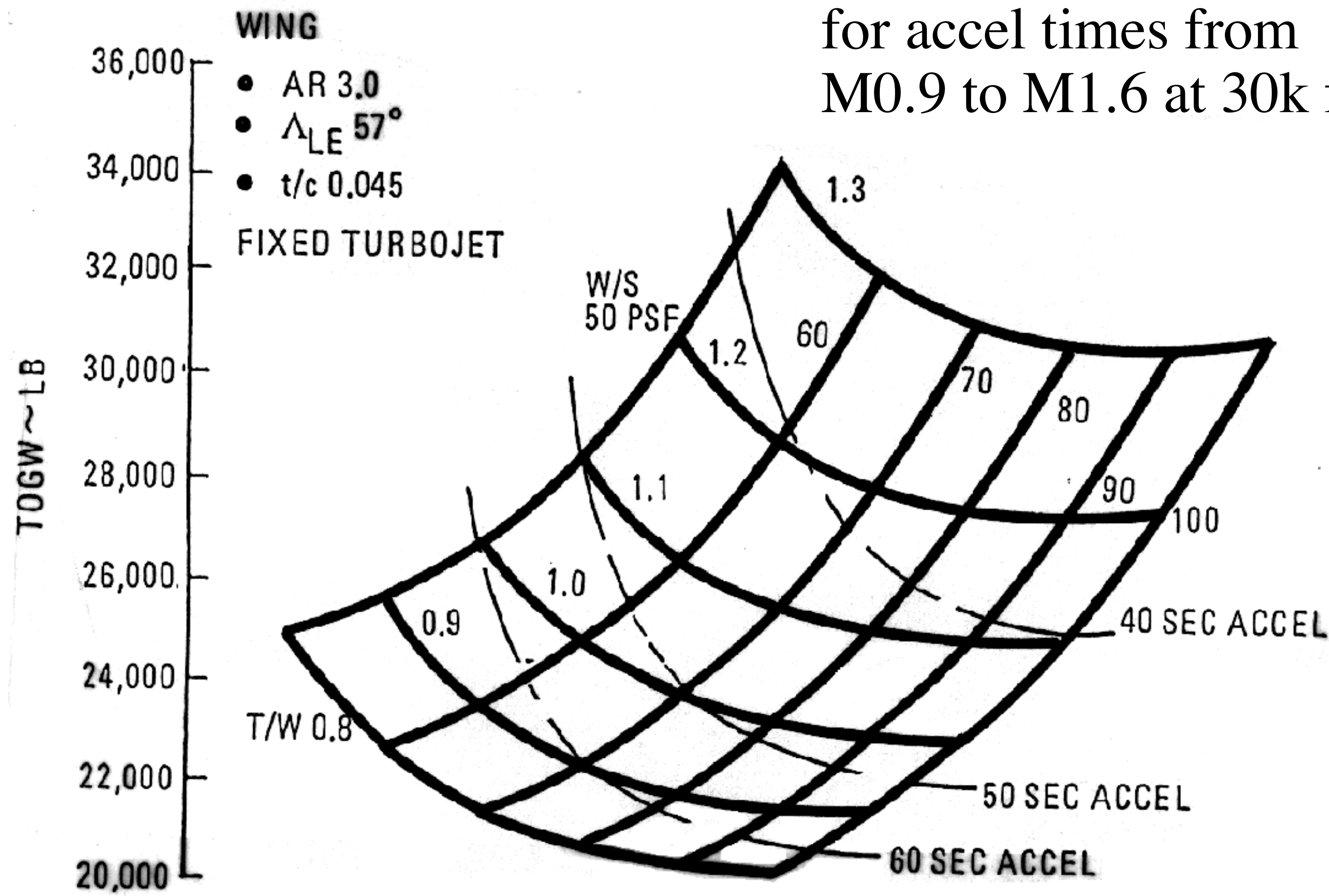
Carpet with Accel Constraints

Accel constraints added for accel times from M0.9 to M1.6 at 30k ft. alt.



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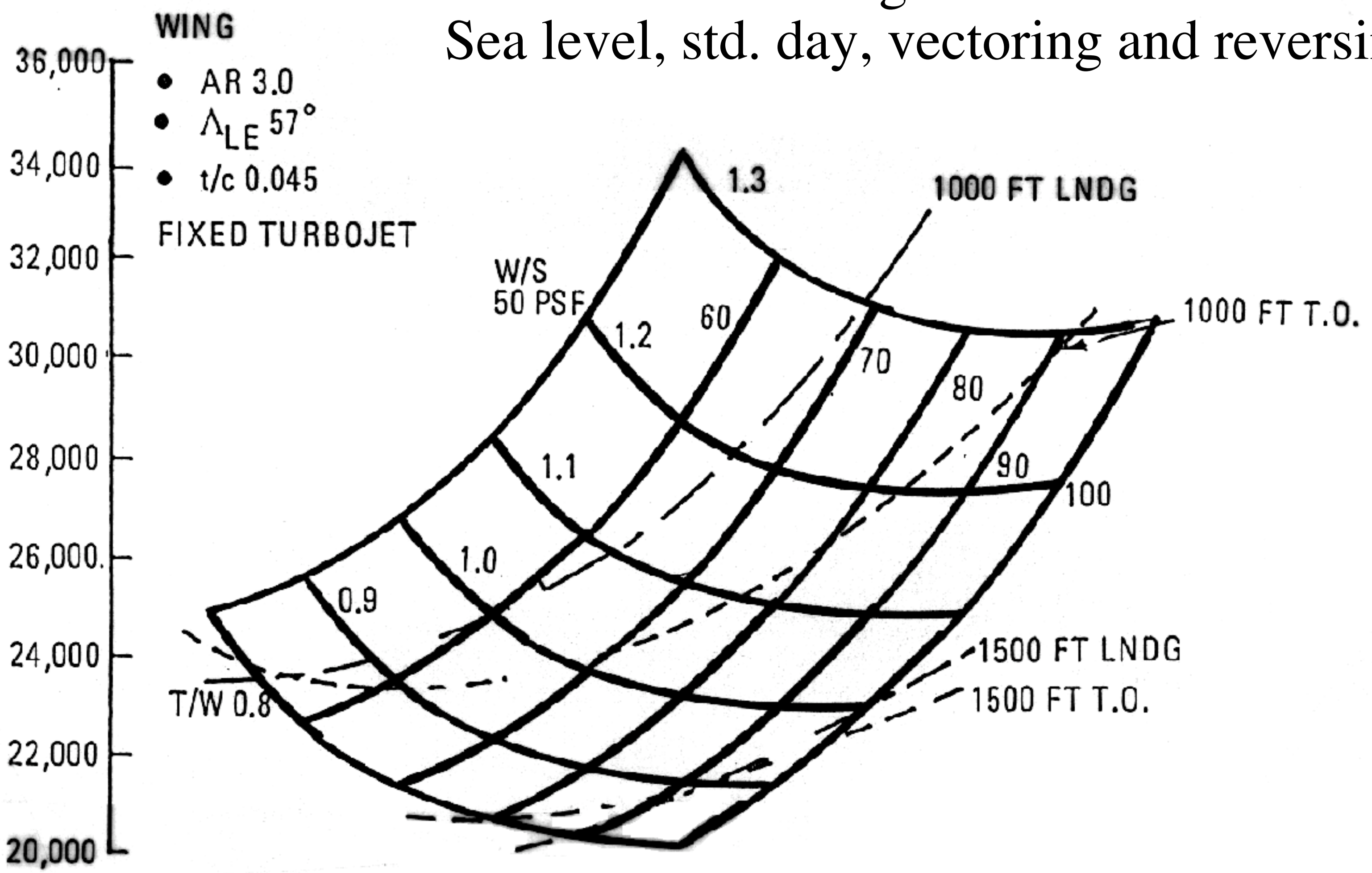
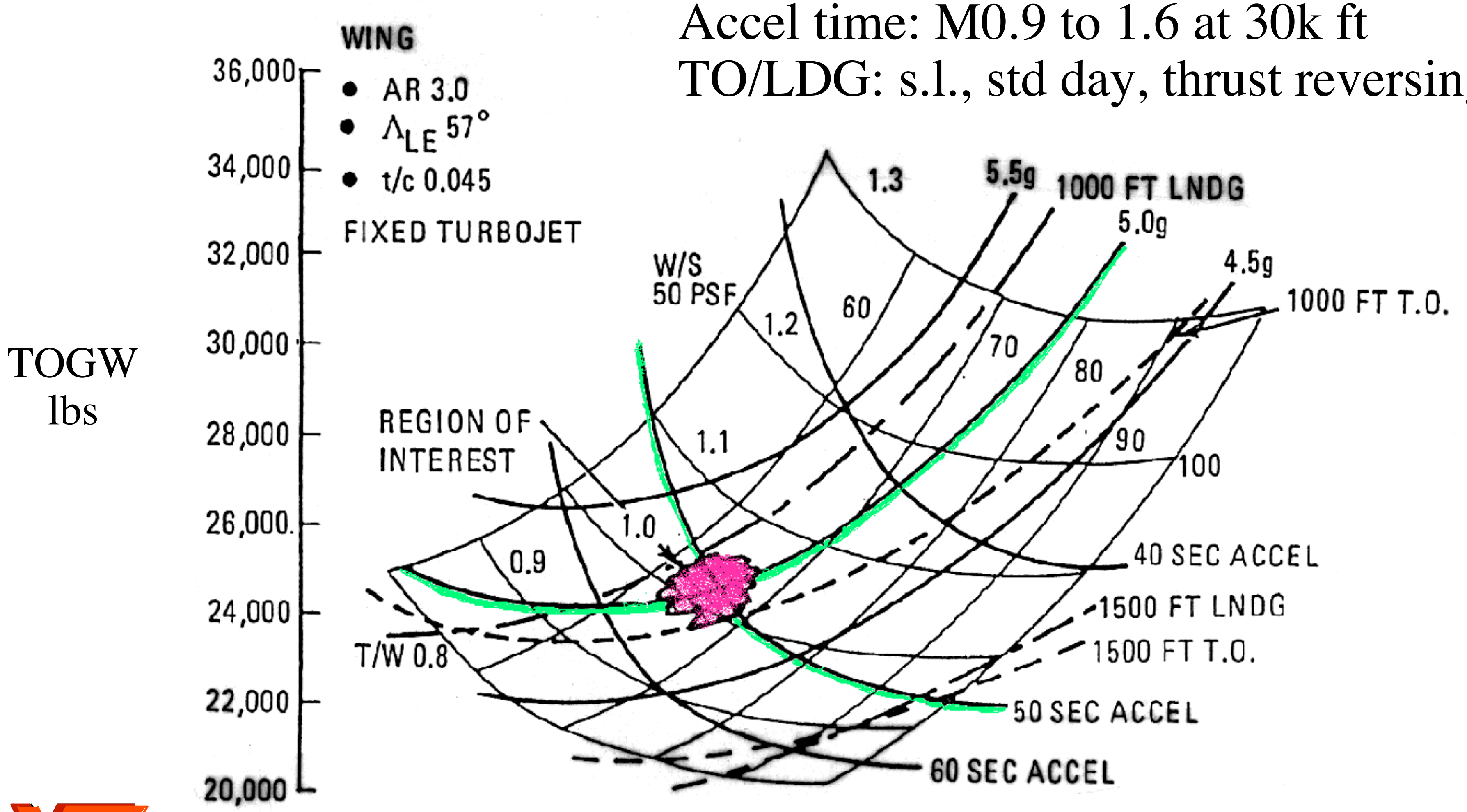
Carpet with Field Performance Constraints

Takeoff and landing constraints added
Sea level, std. day, vectoring and reversing

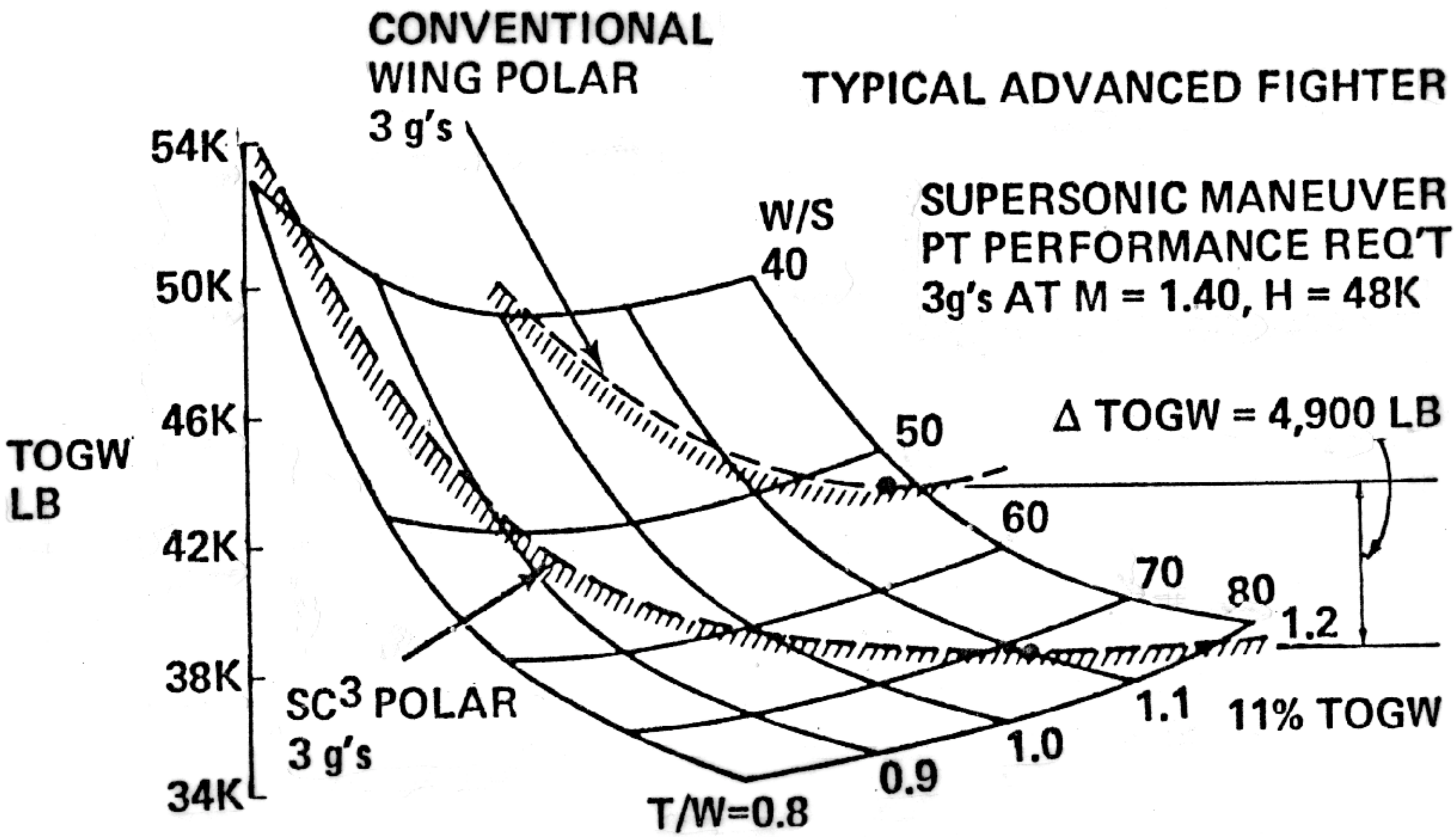


Carpet with All Constraints Included

Sustained *g*'s: M0.9/30k ft
Accel time: M0.9 to 1.6 at 30k ft
TO/LDG: s.l., std day, thrust reversing



Example: Using a Carpet Plot to Assess How to Use Advanced Technology to Improve Maneuver Performance: SC3



Source: W.H. Mason, "A Wing Concept for Supersonic Maneuvering," NASA CR 3763, 1983

Transport Constraints

There is another important constraint for transports:

The airplane must meet the initial cruise altitude requirement

- at the initial cruise altitude (about 98% of TOGW), the so-called "top of climb", airplane must still have a specified rate of climb (500 or 300 ft/min)

According to the book by Jenkinson, Simpkin and Rhodes, *Civil Jet Aircraft Design*,

- Twin-engine aircraft are likely to be second-segment climb critical
- Four-engine aircraft are likely to be climb critical (top of climb performance)

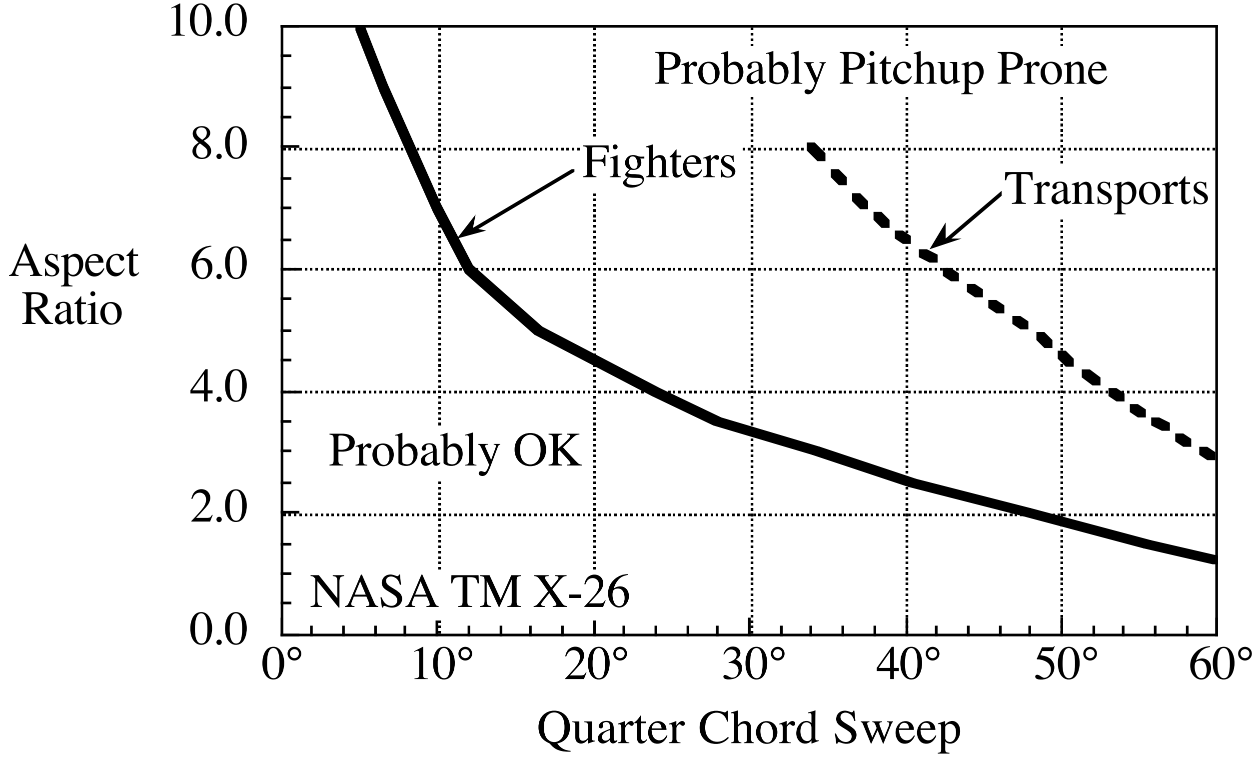
To Conclude:

- You are now equipped to *think* about aircraft design
- We've covered the basic physics dictating selection of aircraft weight, wing and engine size
- We've explained the basic carpet and thumbprint methods to understand effects of constraints, comparison of concepts, and design tradeoffs
- Even major aircraft companies have problems doing the tradeoffs scientifically: lots of bias and prejudice (they wouldn't admit it - but that's part of the reason for the evolutionary aircraft development we see)
- The next step: How to get your ideas on paper, and done so you can tell if they make sense

Wing Planform/Tail Location Are Not Arbitrary
Pitch-Up Limits Planform Selection

Pitching moment characteristics as separation occurs must be controllable. Requires careful aero design. Horizontal tail location is critical

historical trends from early wind tunnel data



Note: DATCOM has a more detailed chart

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