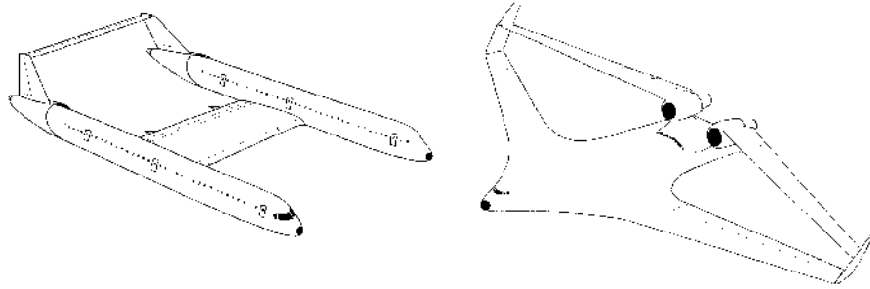


## Classical Aircraft Sizing II

W. H. Mason



Advanced Concepts from NASA TM-1998-207644

### Previously (Sizing I)

- Mission definition
- Basic Sizing to Estimate TOGW
- Examples

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

- Federal Air Regulations (**FARs**) 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!*



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## 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



[see the class web page for a link to the FARs](#)

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## Takeoff Requirements

<u>Item</u>	<u>MIL-C5011A</u>	<u>FAR Part 23</u>	<u>FAR Part 25</u>
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) 3% @ $V_{CL}$ (OEI)
Gear up:	100 fpm @ SL (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	$\mu = 0.025$ * see discussion on next slide	not specified	not specified



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AEO: all engines operating, OEI: one engine inoperative  
from Nicolai, *Fundamentals of Aircraft Design*, 1975  
See Raymer, App. F,

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## 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



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## 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:

<u># of engines</u>	<u>climb gradient (CGR)</u>
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



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## CTOL Landing Requirements

<u>Item</u>	<u>MIL-C5011A (Military)</u>	<u>FAR Part 23 (Civil)</u>	<u>FAR Part 25 (Commercial)</u>
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

<u># of engines</u>	<u>climb gradient (CGR)</u>
4	2.7%
3	2.4%
2	2.1%

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



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## 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



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## 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):

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

$K_T$  – technology factor

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

$W_{TO}$  – TOGW

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



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+ standard variables -  $t/c$ ,  $\Lambda$ ,  $\lambda$ ,  $AR$ ,  $S$

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## Regrouping the Weight Equation:

$$W_{WNG} = 3.08 K_T \left( \frac{K_{PIV} N W_{TO}}{(t/c)} \left[ 1 + \tan^2 \Lambda_{c/2} \right]^2 \times 10^{-6} \right)^{.593} (1 + \lambda)^{.89} b^{1.78} S_W^{-.149}$$

Drivers: • thickness,  $t/c$

- span,  $b$
- sweep,  $\Lambda$
- Wing area,  $S$  (different for fixed  $AR$  or  $b$ )
- taper,  $\lambda$
- TOGW ( $W_{TO}$ )

for low wing weight: • thick wings ( $t/c$  large)

- low span ( $b$  low)
- high taper ( $\lambda$  small)
- low sweep ( $\Lambda$  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  $\rho$ ),  $AR$ ,  $E$  ( $L/D$ )

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



Here: HIGH  $W/S$  is good

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## Wing Loading Considerations (Cont'd)

### Sustained Maneuvering

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

### Takeoff

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

### Landing

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



Here: LOW  $W/S$  is good

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## 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*

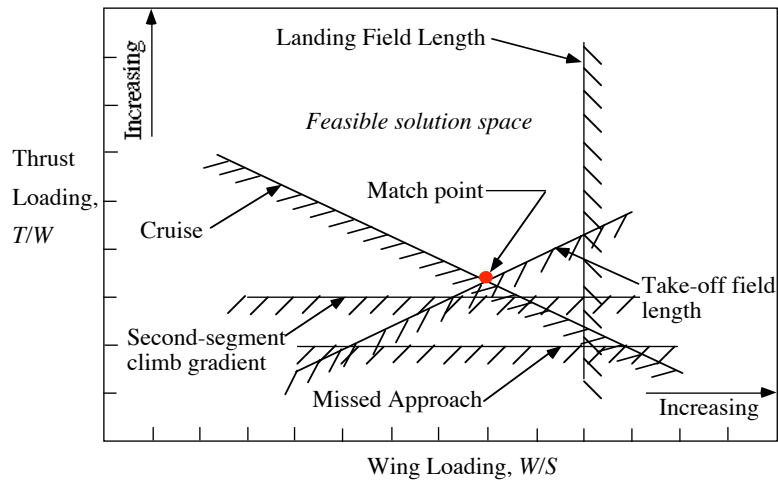
- putting all the constraints on the plot lets you select the best combination

*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



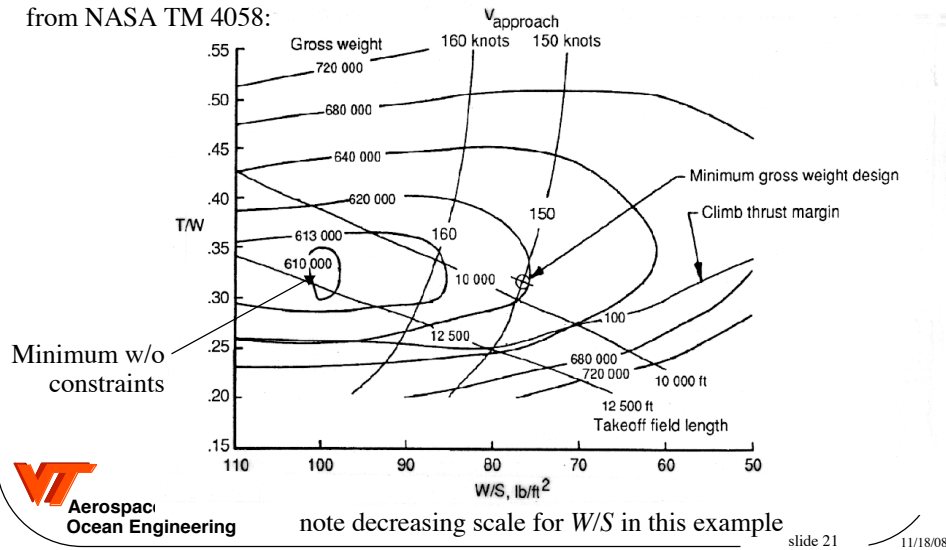
## Tradeoffs and Parametric Studies

- 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:



## Example of Constraint Lines

(approximate examples, be able to derive your own)

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

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

$$\text{Cruise } (T = D): \quad T/W = q \frac{C_{D0}}{(W/S)_{\text{cruise}}} + \frac{(W/S)_{\text{cruise}}}{q \pi A R E}$$

Climb gradient requirements:

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

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

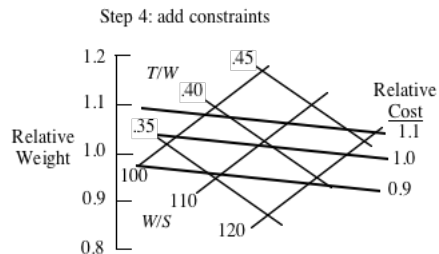
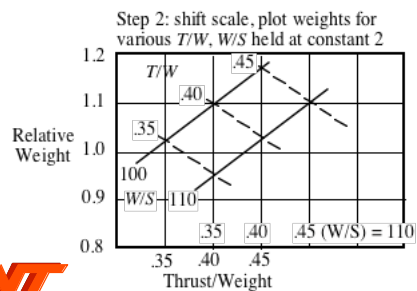
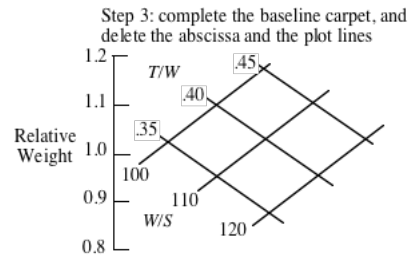
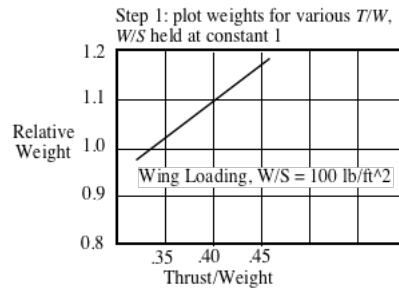
Note: convert  $T/W$  to  $M=0, h=0$  values,  $W/S$  to takeoff values,  $N$  is the number of engines, where we assume one engine out is the critical case, CGR is the climb gradient,  $q$  implies best altitude, Mach, and  $L/D$  should be for correct flight condition.

## 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



## An Example Using Carpet Plots

Examine:

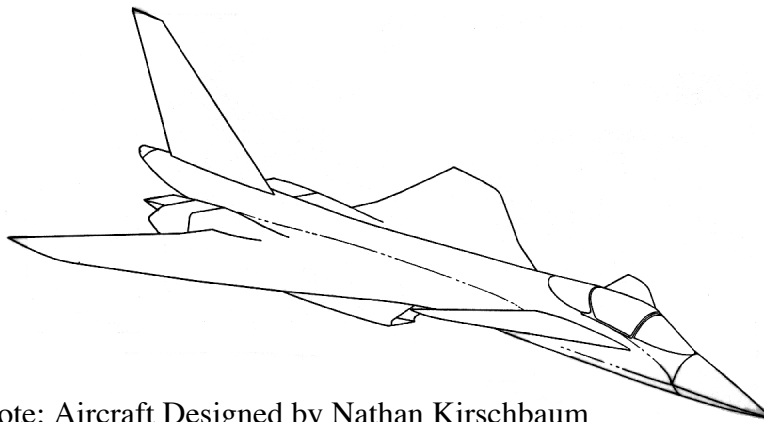
- $W/S$  - the Wing Loading
- $T/W$  - the Thrust Loading

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

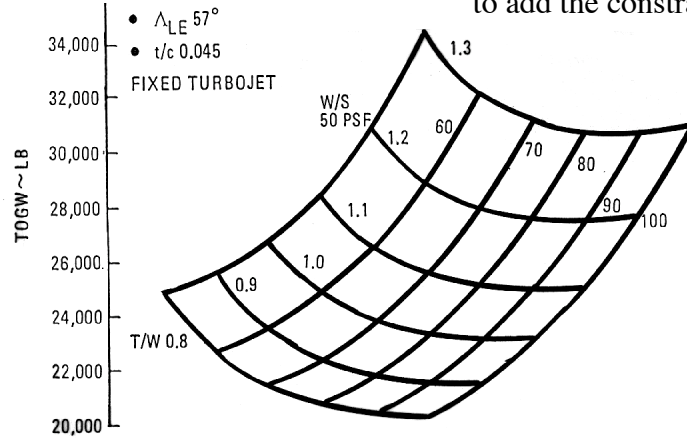
## The Example Design: A Supersonic Fighter



Note: Aircraft Designed by Nathan Kirschbaum

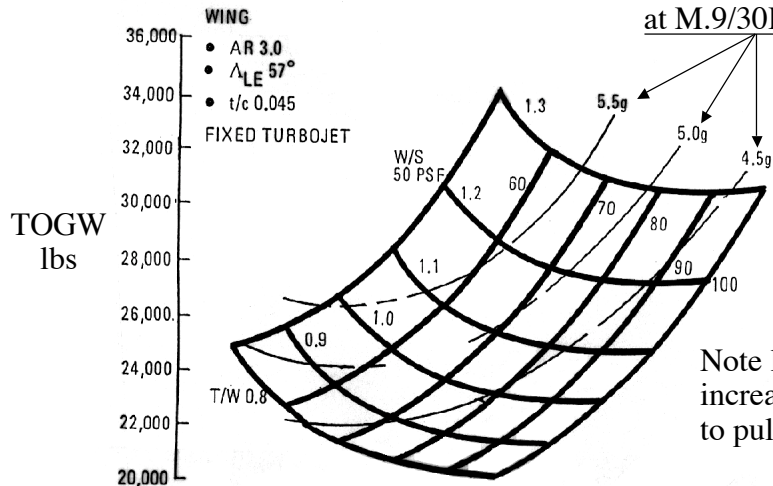
## Basic Carpet (each point is a solution for the given mission)

The baseline chart, ready to add the constraints



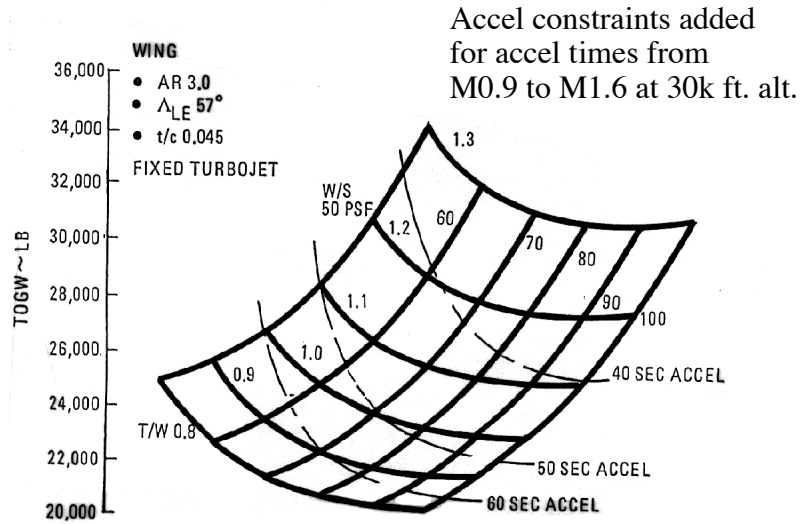
## Carpet with Transonic Maneuver Constraints

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

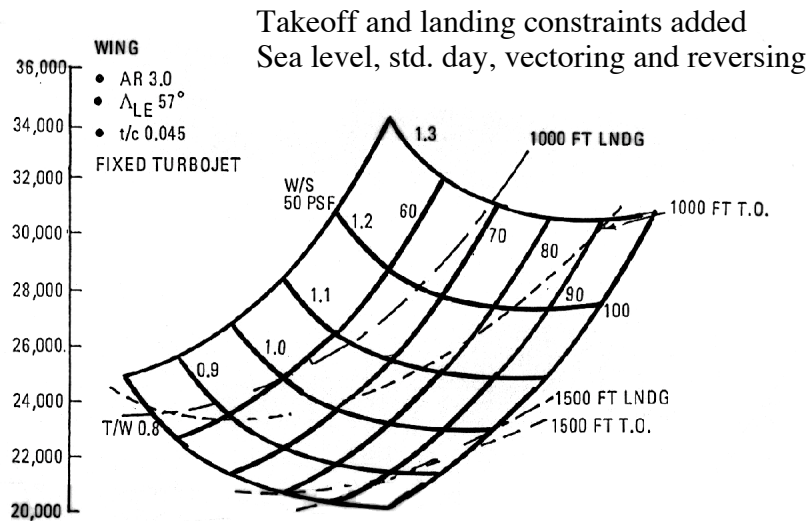


Note large weight increase required to pull more  $g$ 's

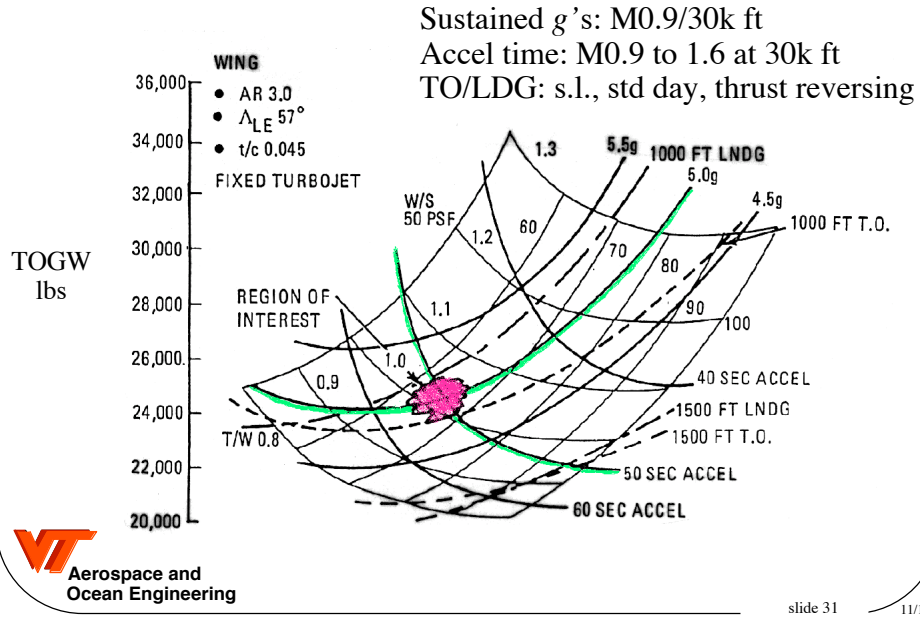
## Carpet with Accel Constraints



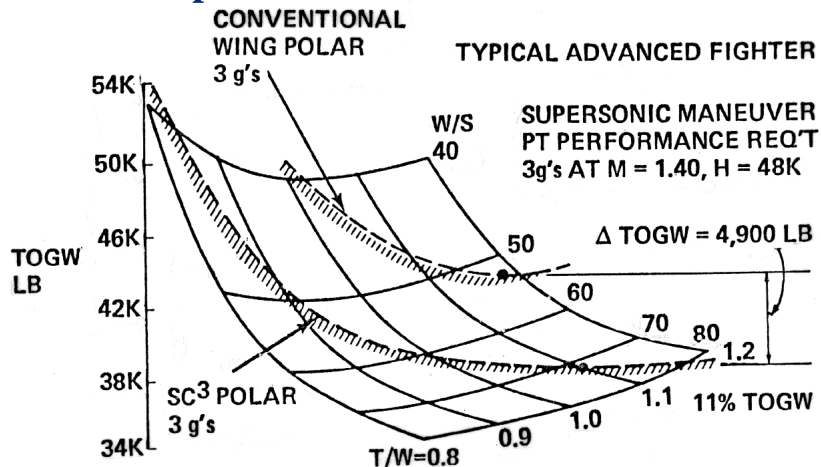
## Carpet with Field Performance Constraints



## Carpet with All Constraints Included



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



## 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*,

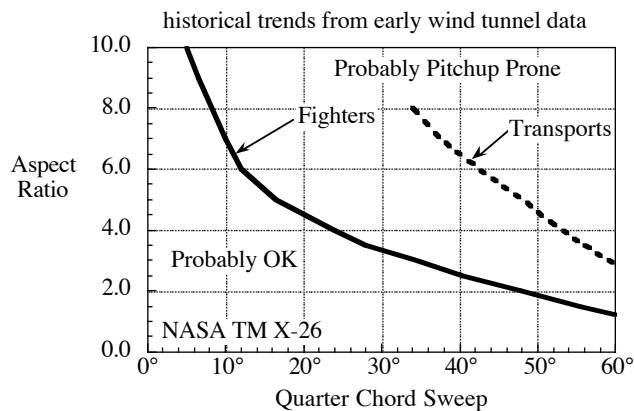
- Twin-engine aircraft are likely to be second-segment climb critical
- Four-engine aircraft are likely to be climb critical (top of climb performance)

## 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*



Note: DATCOM has a more detailed chart