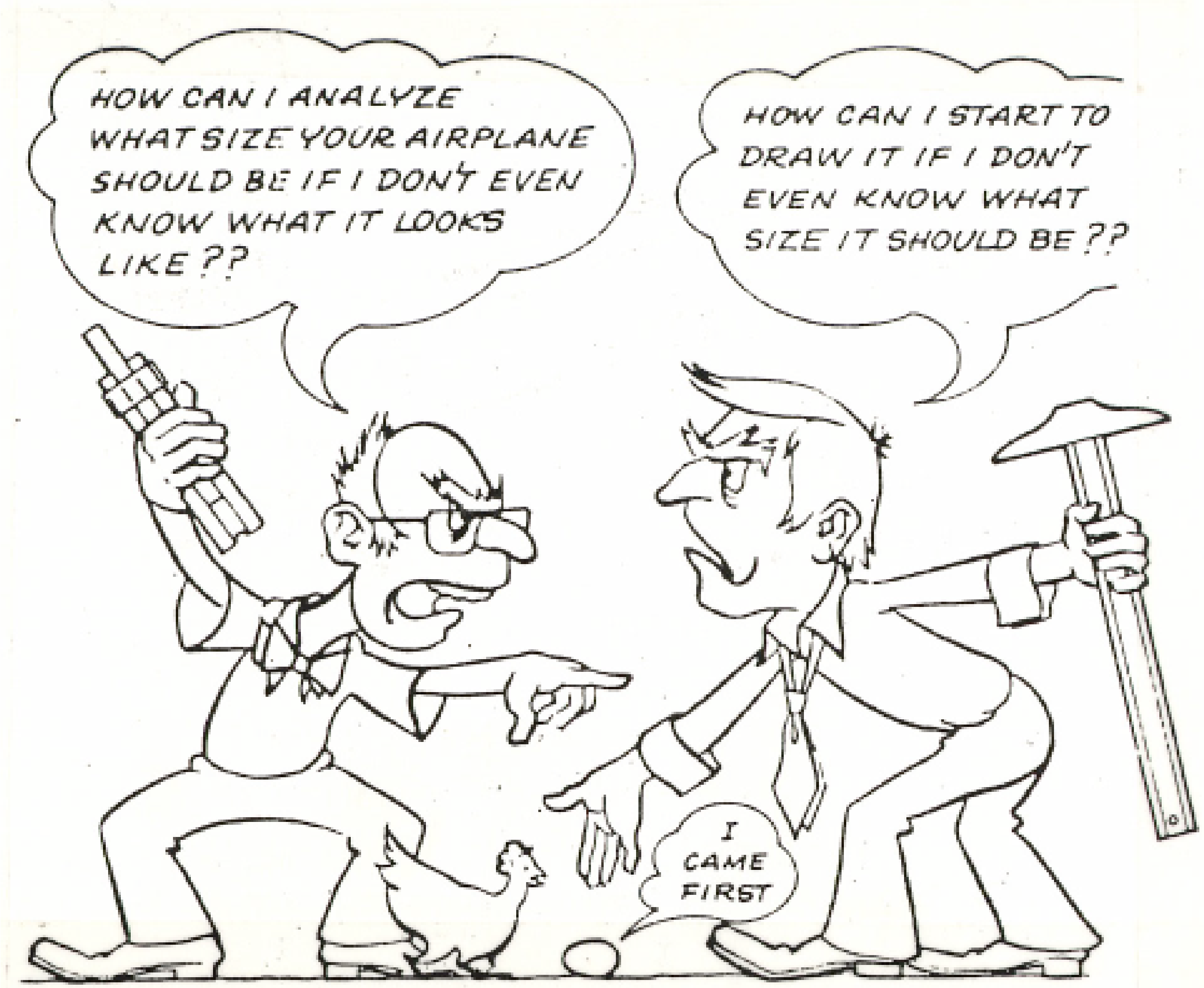
Classical Aircraft Sizing I



from Sandusky, Northrop

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Which *is* 1st?

You need to have a concept in mind to start

The concept will be reflected in the sizing
by the choice of a few key parameters.

Then what?

- 1st estimate the TOGW of the airplane
- 2nd, estimate the *W/S* and *T/W*
- 3rd, use the mission program to evaluate the design

To Start: Define a Mission

What is this airplane supposed to do?

- How far does it go? How fast?
- What and how much does it carry?
- What are the landing and takeoff requirements?
- Are there any maneuver/accel requirements? (these are known as point performance req'ts)
- What MIL or FAR req'ts must be satisfied?

Taken together, the answers to these questions are known as the **Mission Statement**, and also imply that you think of concepts to do the job

Note: the web slides contain more charts. Fill in details

Basis for Sizing

- Many Possibilities for the Selection Criteria
- Possible Choices:
  - minimum life cycle cost
  - " flyaway cost
  - " direct operating cost
  - " fuel cost
  - " **take off gross weight (TOGW)**
- Cost is the real selection criteria, but hard to estimate
- For a given class of aircraft, aircraft cost/lb is similar

  ∴ min weight is a good choice for comparing alternatives

The Importance of Weight Control

$$TOGW = W_{TO} = W_{struc} + W_{prop} + W_{fuel} + \underbrace{W_{payload} + W_{systems}}_{W_{fixed}}$$

$$= W_{TO}\left(\frac{W_{struc}}{W_{TO}} + \frac{W_{prop}}{W_{TO}} + \frac{W_{fuel}}{W_{TO}}\right) + W_{fixed}$$

$$or: \quad = \left[1 - \left(\frac{W_{struc}}{W_{TO}} + \frac{W_{prop}}{W_{TO}} + \frac{W_{fuel}}{W_{TO}}\right)\right] W_{TO} = W_{fixed}$$

$$\Rightarrow \quad W_{TO} = \frac{W_{fixed}}{\left[1 - \left(\frac{W_{struc}}{W_{TO}} + \frac{W_{prop}}{W_{TO}} + \frac{W_{fuel}}{W_{TO}}\right)\right]}$$

$$\approx 0.29 \quad \approx 0.15 \quad \approx 0.31$$

Possible Values

Typical:

$$W_{TO} = \frac{W_{fixed}}{(1 - .75)} = 4 \cdot W_{fixed}$$

4 is the Growth Factor!

More Precise Weight Definitions

- Standard nomenclature important
- FAR, MIL STD & Technical Societies define, see Torenbeek, Chap. 8, pg 263-275 (quote at specified loading and *cg*)

  - *eventually you will make a detailed weight statement*-

- In 1st cut sizing we use Nicolai's definitions:

  $TOGW = W_{fuel} + W_{fixed} + W_{empty}$

  W_{empty}: basic structure and propulsion

  W_{fixed}: all items that can be removed and the a/c would still be ready to fly, divided into two parts,

  a) non-expendable (crew + equipment)

  b) expendable: passengers, baggage, cargo
  bombs & missiles, etc.

1st Cut Sizing

Several Methods Available:

- Nicolai, Chap. 5
- Roskam, Vol. 1 (both Jets and Props)
- Raymer, Chap. 6 and 19 (Chap. 3 too crude, but read)
- Loftin, Chap. 3 and 4 (Jet) and Chap. 6 and 7 (Prop)
  (available on class web page - >400M)
- Torenbeek, pp. 144-148, 171-180

We will use Nicolai's Method in Class Examples

Note: books on reserve in the Architecture Library: see Schetz on the Library reserve page

How to Start?

Fuel Available = Fuel Required

or, following Nicolai, With a given TOGW, subtract the fuel and payload. Is the weight left enough to build an airplane?

Available Empty Weight, *WEmptyAvail*

= Required Empty Weight, *WEmptyReqd*

WEmptyReqd comes from statistics at 1st Iteration,

In code this is

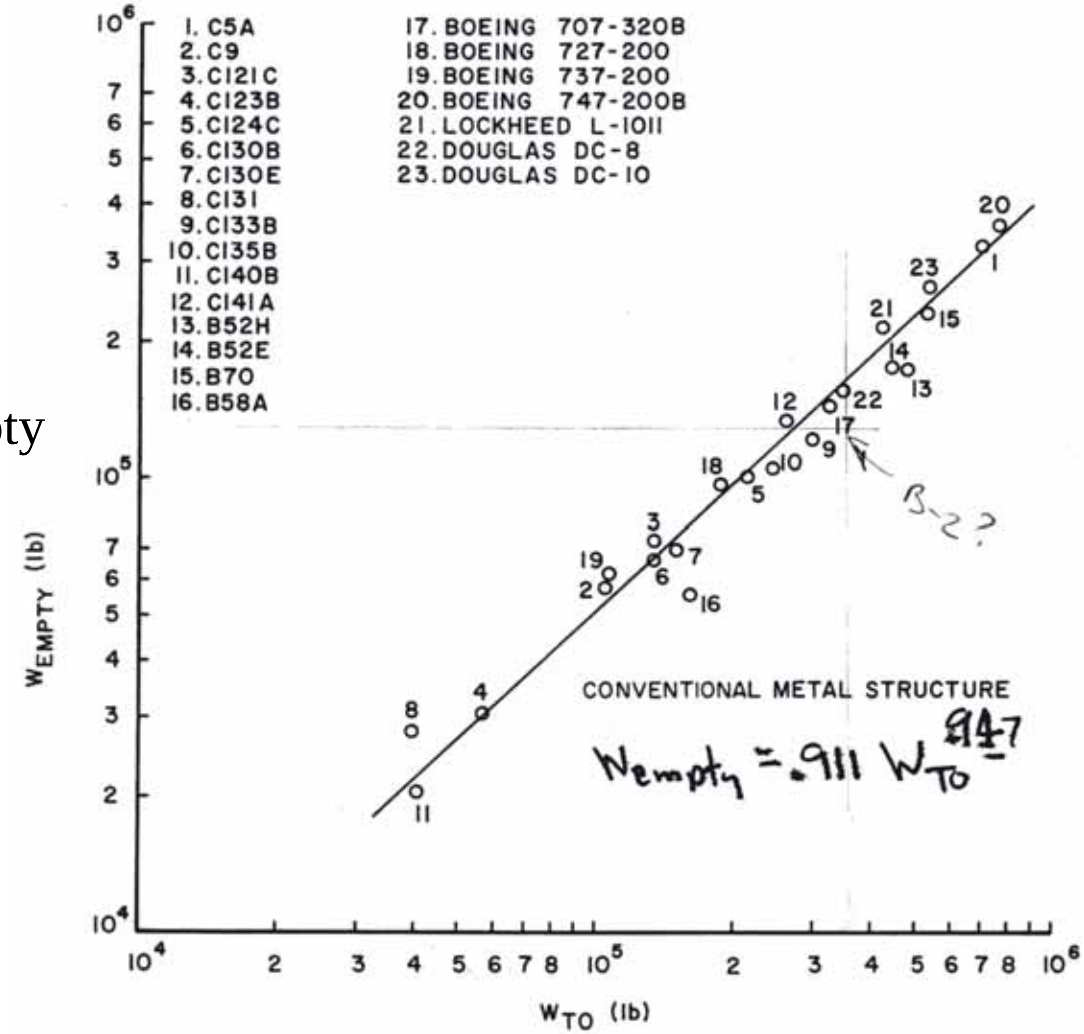
$$WEmptyReqd = KS \times A \times TOGW^{B}$$

A,B: come from fit of data for similar designs

KS: structural technology factor

Typical
Empty Weight Req'd—Takeoff Weight Correlation

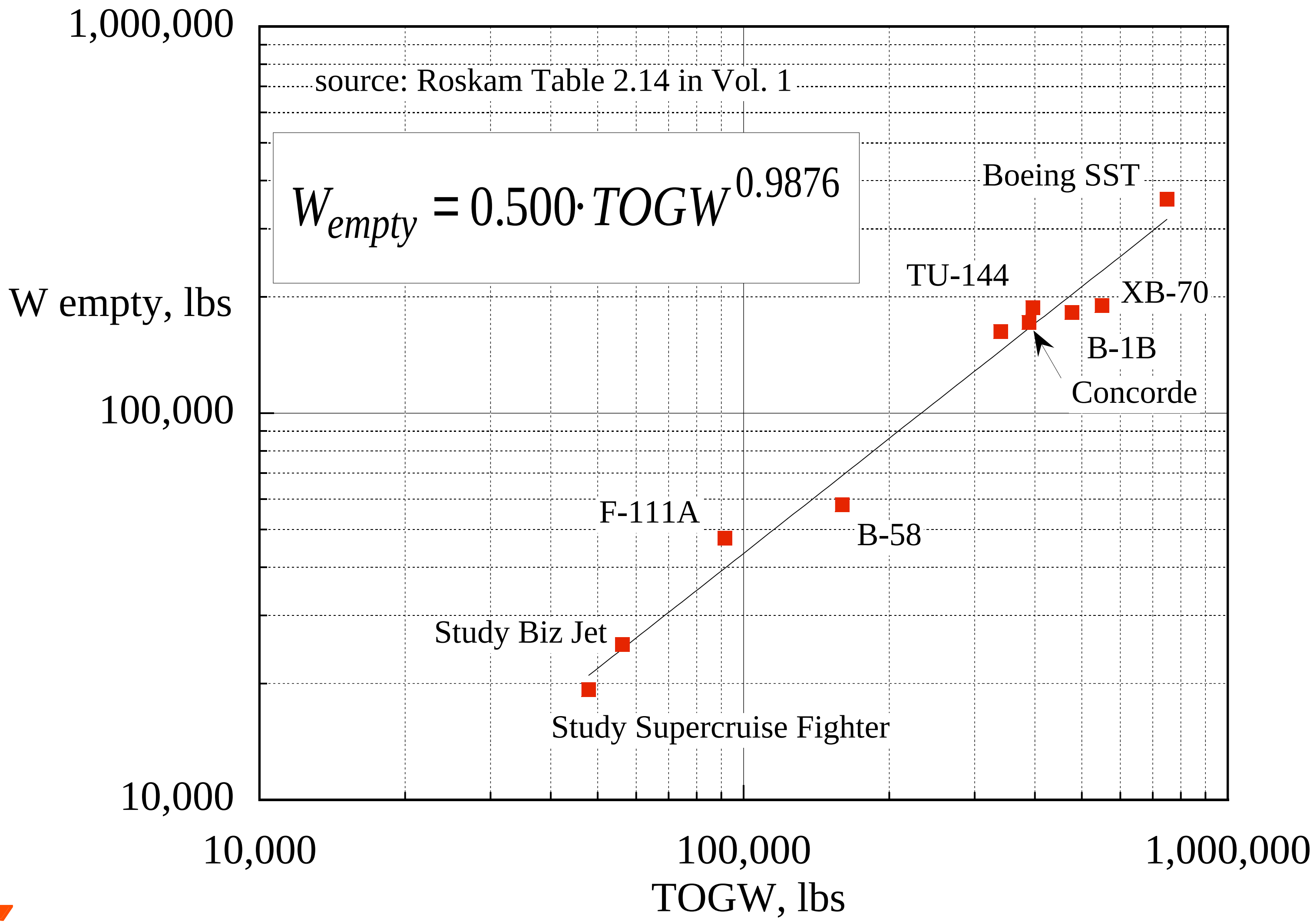
Wempty



TOGW

from Nicolai, pg 5-4 (old statistics)

Specific Example: Supersonic Transport



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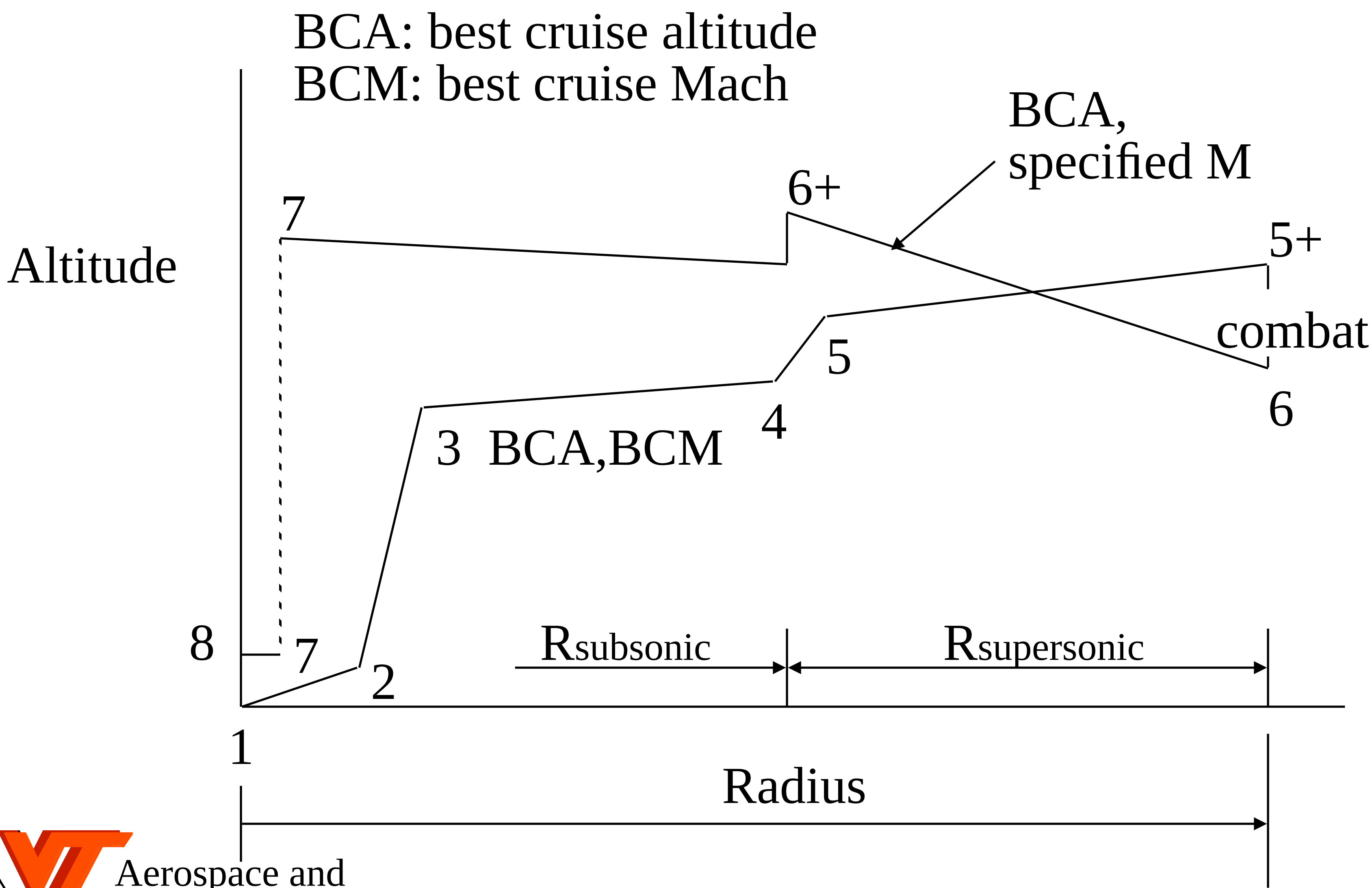
To Get *WEmptyAvail*, 1st Define Mission Segments



Mission Phase Definitions

(follow Nicolai, except add supersonic segments)

Phase	
1-2	engine start and takeoff
2-3	accelerate to subsonic cruise velocity and altitude
3-4	subsonic cruise out
4-5	accel to high speed (supersonic) dash/cruise
5-5+	supersonic cruise out
	combat (use fuel, expend weapons)
6-6+	supersonic cruise back
6+ -7	subsonic cruise back
7-8	loiter
8	land

Note: for Military descent:
No credit for time, fuel or distance

Mission Program

- Aircraft Companies, Gov't., etc. have ***Mission Programs***
- We have a mission program written for MATLAB

  - based on Sid Powers' *BASIC Aircraft Performance*
  - originally by Mike Morrow
  - then further developed by Dzelal Mujezinovic
  - currently Chris Cotting

- You need detailed propulsion data (and aerodynamics), well as weight, etc. to "fly" the mission.

Now to Get *WEmptyAvail*

- Compute fuel fraction for each segment of mission
- For Range segments:

$$R_{i+1} = \frac{V}{sfc}\left(\frac{L}{D}\right)\ln\frac{W_i}{W_{i+1}}$$

or

$$\frac{W_{i+1}}{W_i} = e^{-\frac{R \cdot sfc}{V(L/D)}}$$

For Loiter Segments:

$$E = \frac{1}{sfc}\left(\frac{L}{D}\right)\ln\frac{W_i}{W_{i+1}}$$

or

$$\frac{W_{i+1}}{W_i} = e^{-\frac{E \cdot sfc}{(L/D)}}$$

Note: Watch Units!

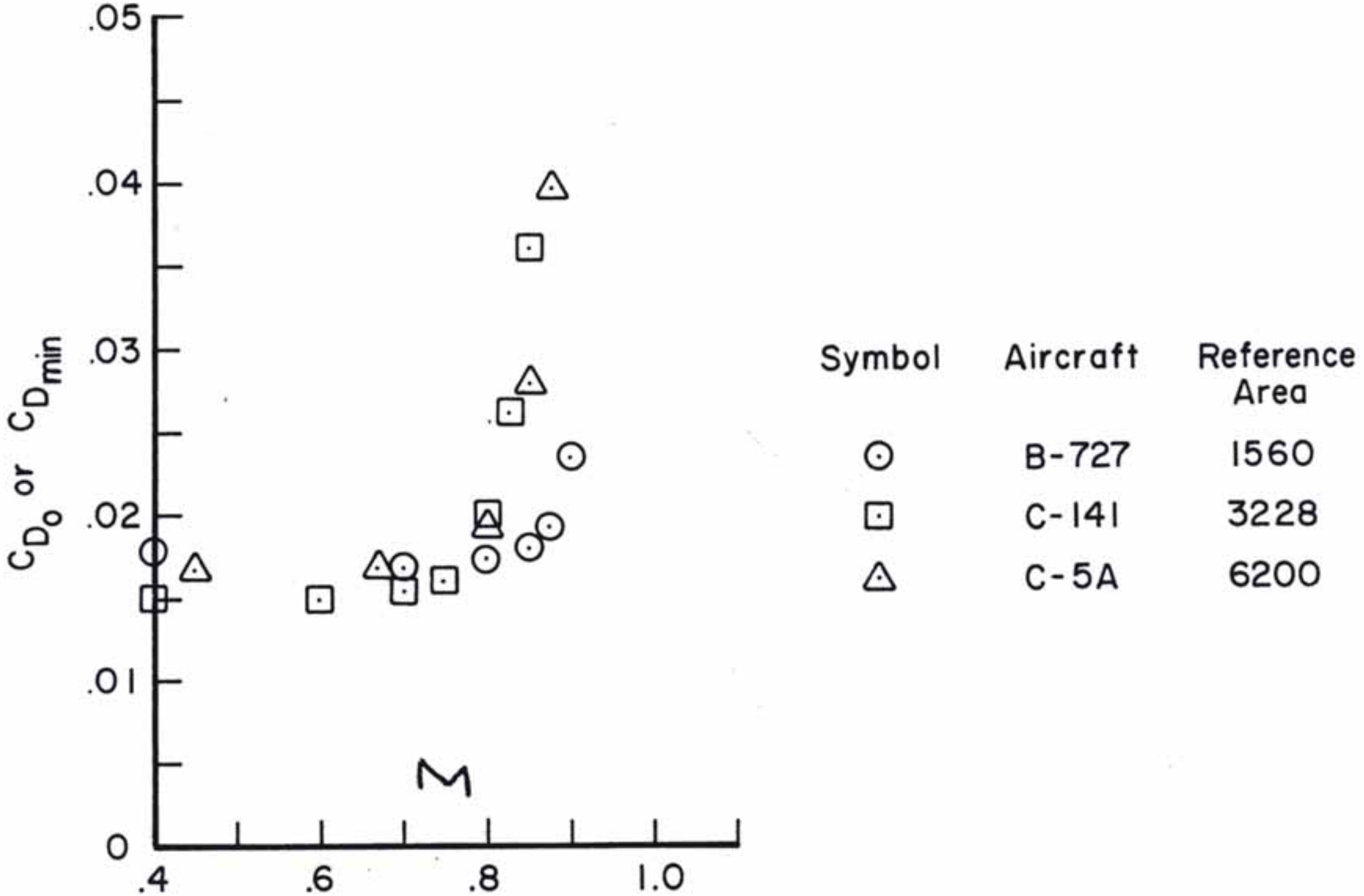
Where to get values to put in formulas?

With your vehicle concept in mind:

- use historical data for *L/D* max, requires C_{D0}, *E*, *AR*
- *sfc*: use engine spec. or see propulsion text
- Velocity: fly just before drag rise (0.7 to 0.8 Mach)
- Following charts provide some info

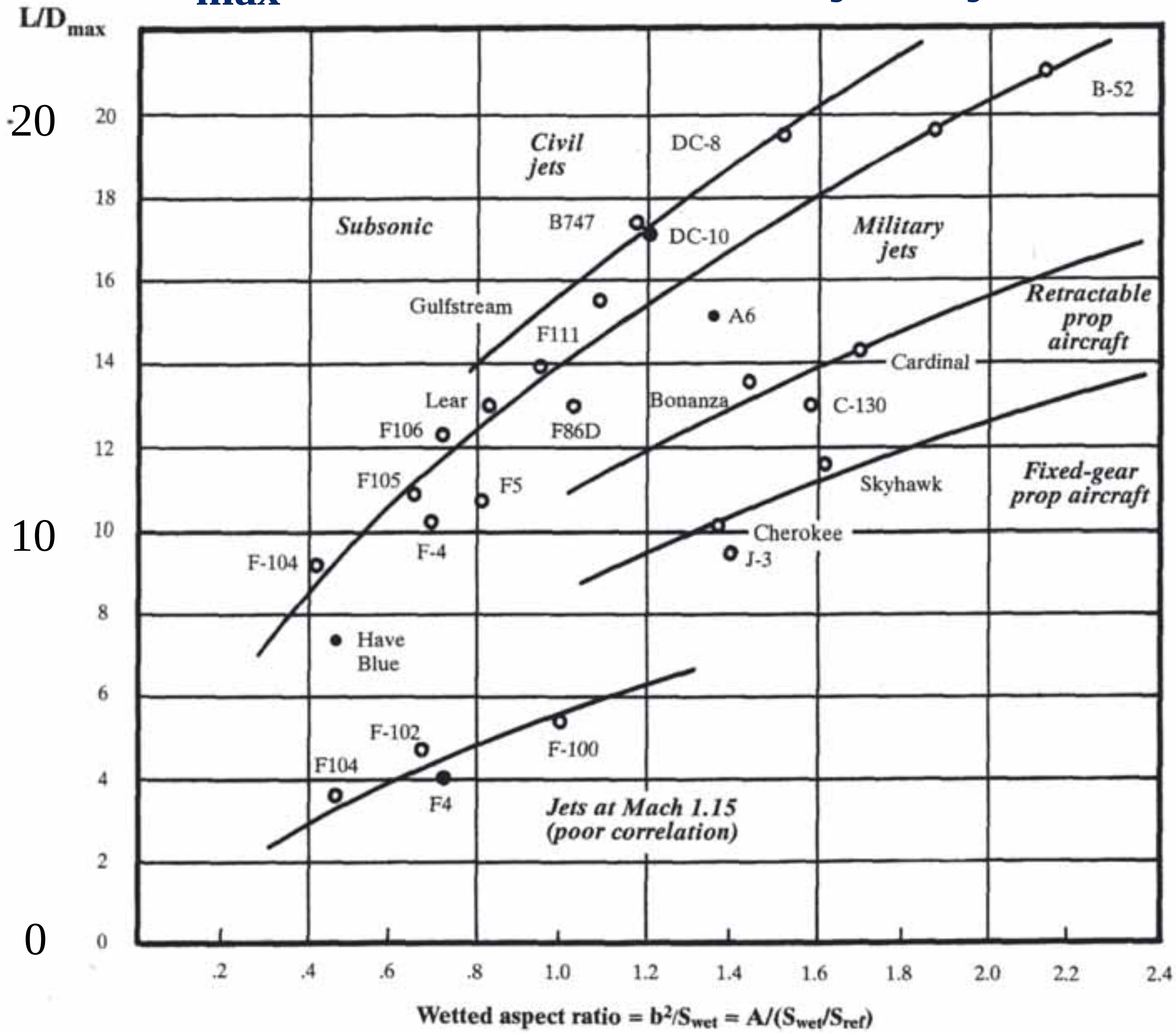
(or see Raymer, Torenbeek, Nicolai, Roskam, *etc*. for summaries and statistics)

Typical Zero Lift Drag Values for Transports



from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

L/D_{max} data correlation by Raymer

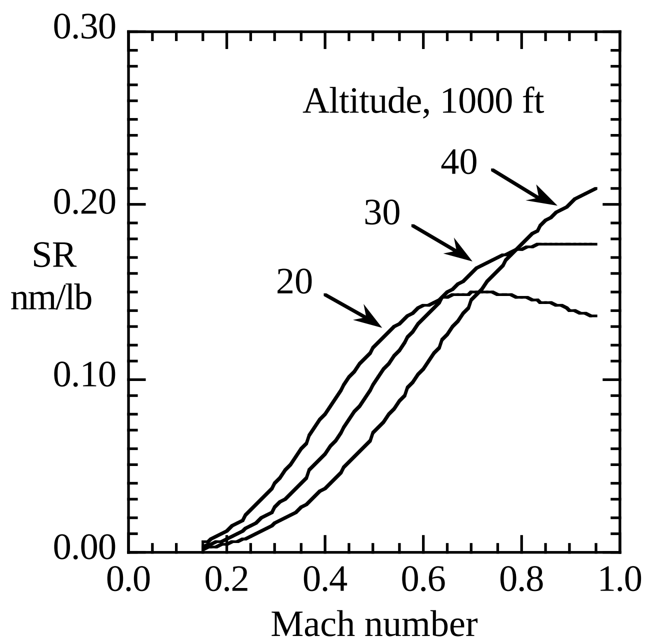


source: Raymer, *Aircraft Design: A Conceptual Approach*

Speed and Altitude: Review of Best Range

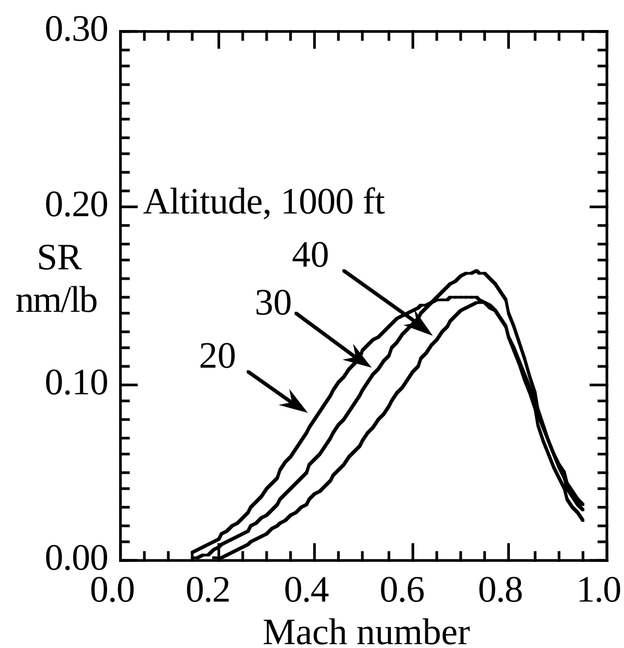
(consider specific range, SR)

Drag Rise Not Included



Best Altitude/Mach
Increase Without Bound

Drag Rise Included



Drag rise (compressibility)
leads to distinct optimum
speed and altitude

Note: Study of impact of technology integration requires operation at BCA/BCM

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based on a figure in Shevell, *Fundamentals of Flight*

For other parts of the Mission:

- Startup, Takeoff: estimate 2 1/2 to 3 % of TOGW
- Climb and Accel: Use correlation chart or Raymer Eqn.
- Accel to High Speed, Use Chart Again
- Combat: # of minutes max power, or # of turns:

  Combat Fuel = *sfc* x Thrust x Time

  and:

  $$\dot{\psi} = \frac{g\sqrt{n^2 - 1}}{V}, \quad \text{in radians per sec.}$$

  $$\text{Time} = (\text{no. of turns})(360°) / \dot{\psi}, (\text{in degrees per sec})$$

  - Watch units: Degrees and Radians
- Reserve and trapped fuel must be accounted for

Weight fraction for climb-accel phases

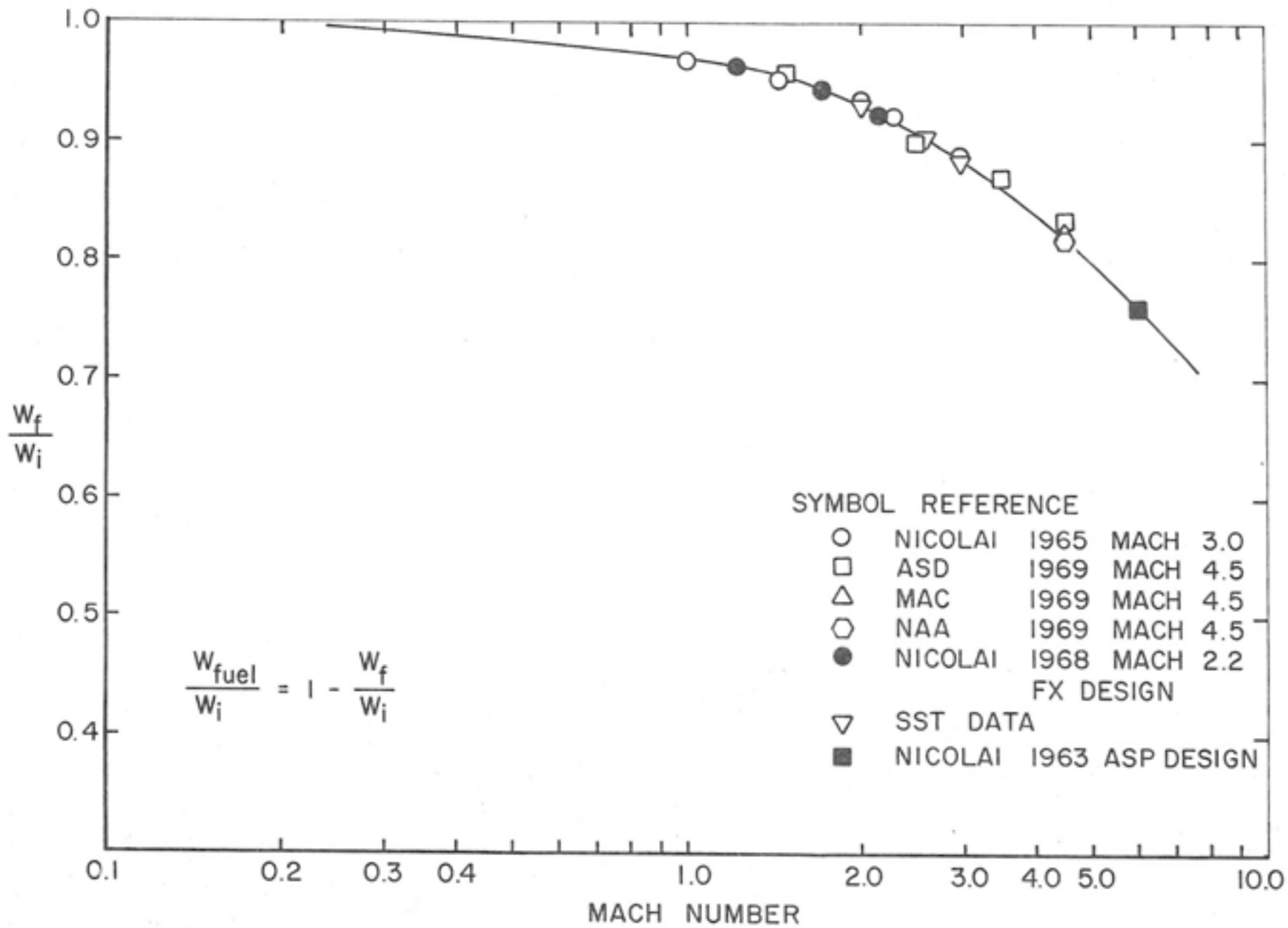

Fig. 5.5 Weight Fractions for Climb-Acceleration Phase

from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

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See also: Raymer, 4th Ed, page 115, eqns. 6.9 and 6.10, and page 582, eqns. 19.8 and 19.9

Actual Computation: Perform an Iteration

1. Assume TOGW
2. Compute *WEmptyReqd*
3. Compute *WEmptyAvail*
4. Estimate a new TOGW

At 1st, these will not agree

$$W_{TO}^{j+1} = W_{TO}^{j} + \Delta\left(WEmptyReqd - WEmptyAvail\right)$$

– where Δ is a relaxation factor to speed convergence (2 for the examples)

5. Go to step 2, and repeat until

$$\left|WEmptyReqd - WEmptyAvail\right| < \varepsilon$$

Example & Use of Fuel Fractions

$$\frac{W_{final}}{TOGW} = \frac{W_{final}}{W_{TO}} = \frac{W_8}{W_1} = \underbrace{\frac{W_2}{W_1}\frac{W_3}{W_2}\frac{W_4}{W_3}\cdots\frac{W_8}{W_7}}$$

fuel fraction for each segment
(must include a step change
if you drop something)

$$W_{fuel} = \left(1 + \frac{W_{\substack{reserve\\fuel}}}{W_{TO}} + \frac{W_{\substack{trapped\\fuel}}}{W_{TO}}\right)\left(1 - \frac{W_8}{W_1}\right)W_{TO}$$

$$= \left(1 + \frac{W_{\substack{reserve\\fuel}}}{W_{TO}} + \frac{W_{\substack{trapped\\fuel}}}{W_{TO}}\right)\underbrace{\left(W_{TO} - W_{Landing}\right)}$$

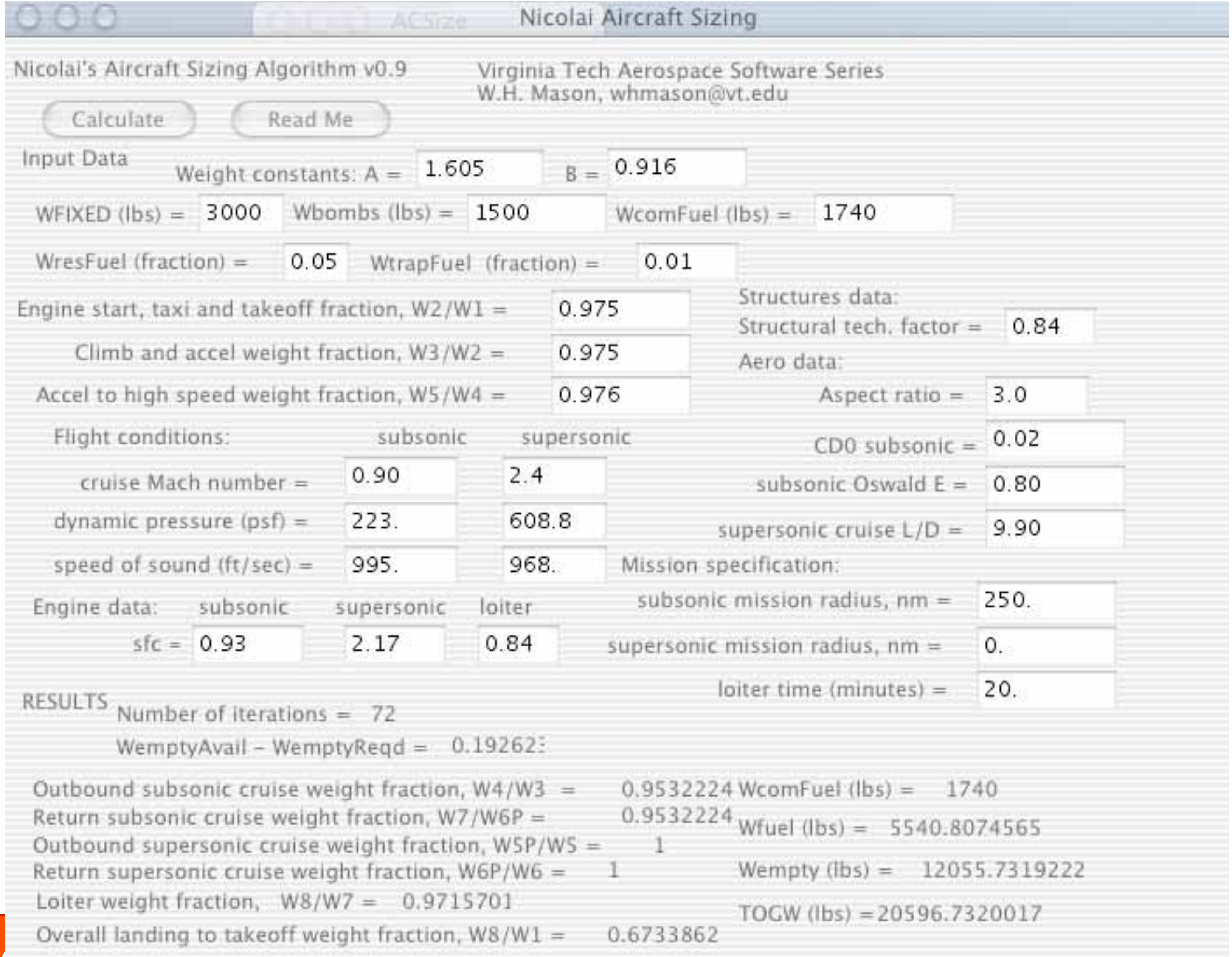
ignores any other weight
loss during mission

$$W_{EmptyAvail} = W_{TO} - W_{fuel} - W_{fixed}$$

see extra notes on web for extension to include bombs dropped, etc.

Our example sizing code acsize.QB

- Originally we had an implementation of this scheme in QuickBASIC(still available on the software page): acsize.QB
- We also have acsweep.QB. It computes lines of *WemptyReqd* and *WemptyAvail*
- Now a REALbasic code (Mac counterpart of VisualBASIC?) version of acsize



Software available from Mason's Software web page

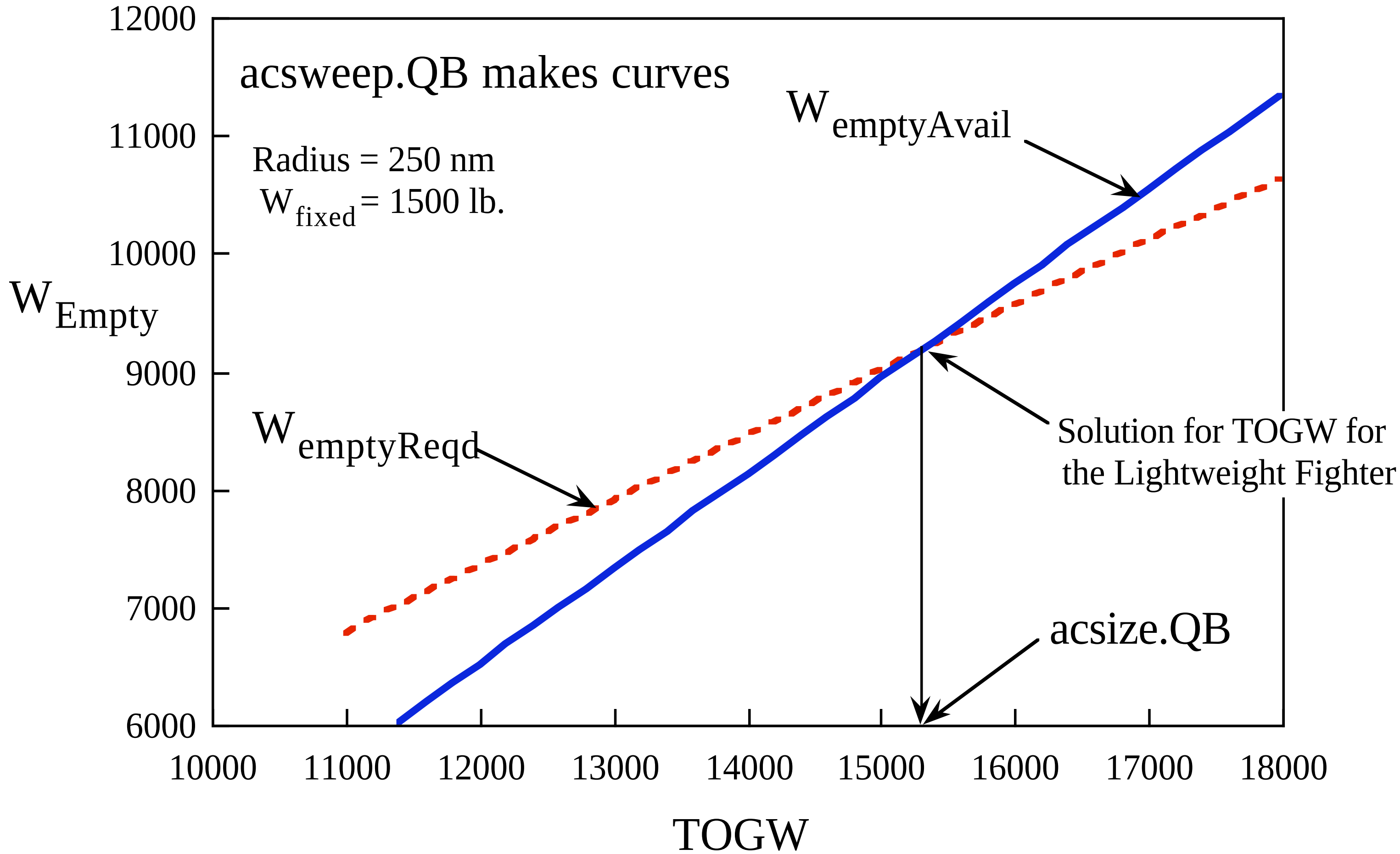
Example: Nicolai's Lightweight Fighter

- 250 nm mission radius
- 4 minutes of max *a/b* at M.9, 30K ft
- one accel from M = 0.9 to M = 1.6 at 30K ft
- 5% reserve fuel
- Crew of One
- Two AIM 9 missiles, one M-61 cannon
- One F100 afterburning turbofan engine

Implies:

- L/D cruise = 9
- sfc = 0.93

Comparison of Required and Available Weights over a range of TOGW



Essentially from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

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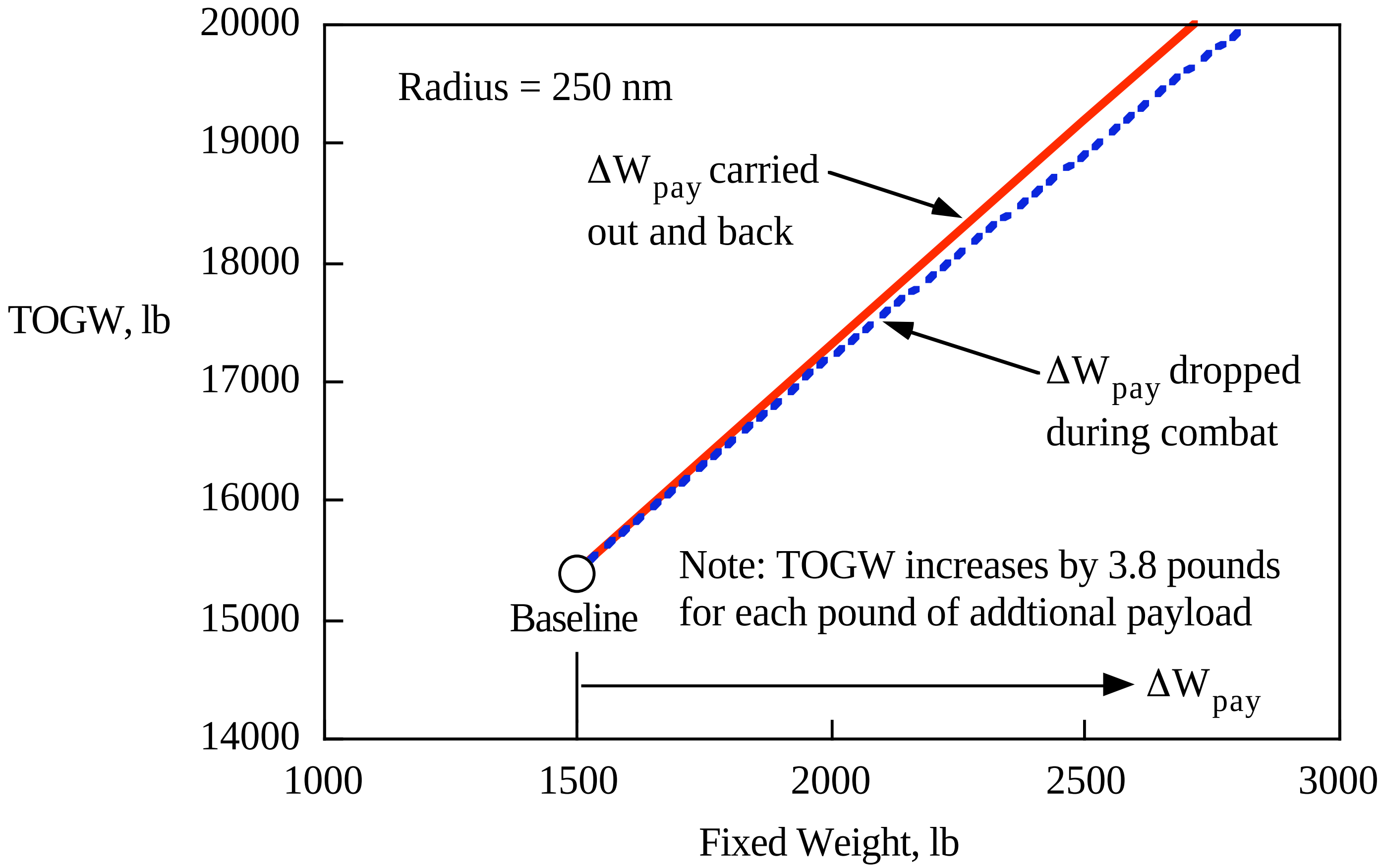
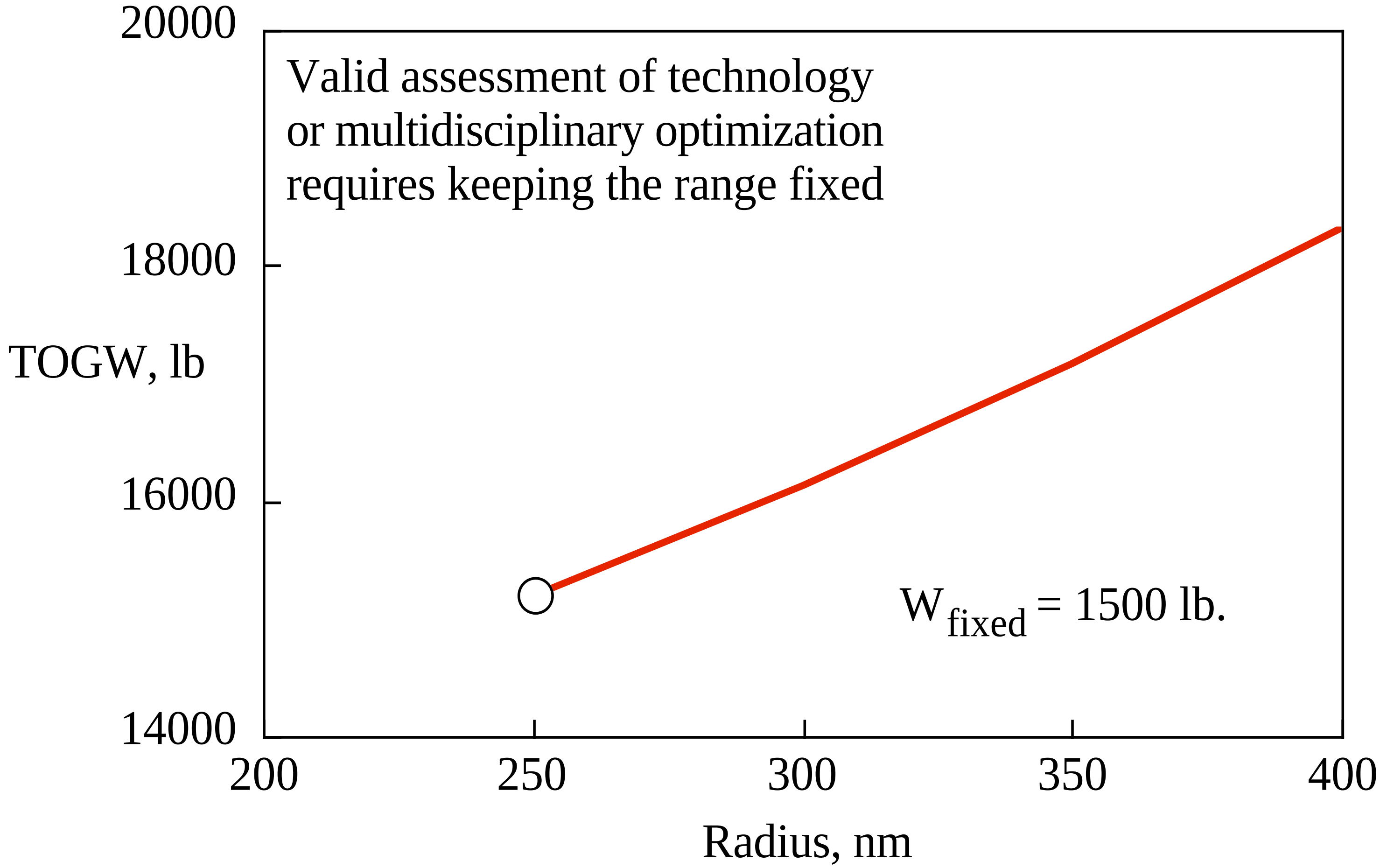
Sensitivity of TOGW to Change in Payload, the Growth Factor



Essentially from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

TOGW Sensitivity to Radius (or Range) Requirement



Essentially from Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975

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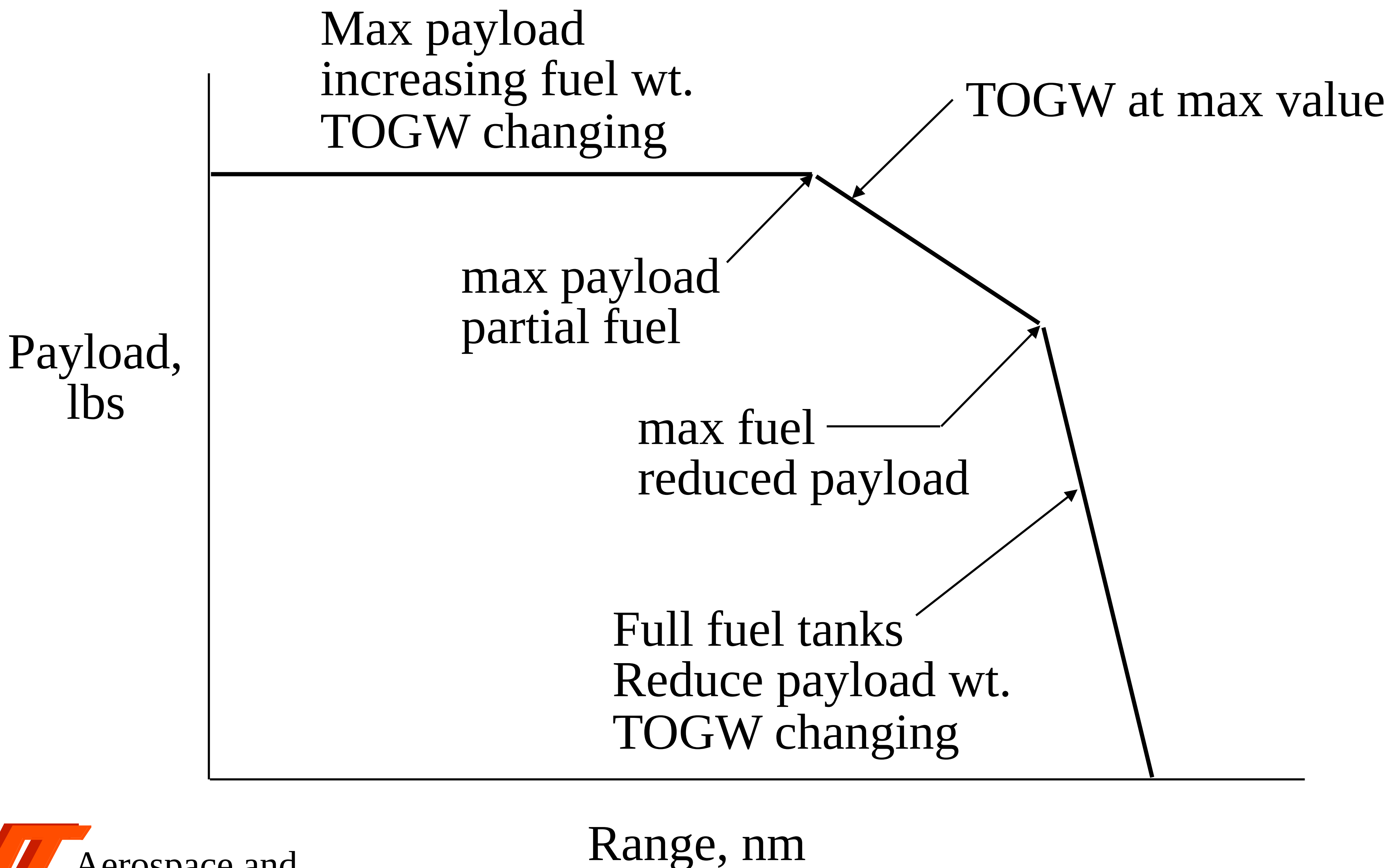
Large Transport Aircraft Example

- the Range-Payload diagram
- comparison with C-5A
  - 6000 nm range
  - 100,000 lb payload
  - *sfc* = .6 @ M=.8, 36,000 ft alt.
  - *L/D* = 17
- examples for increasing range, holding the technology level constant

Range-Payload Diagram

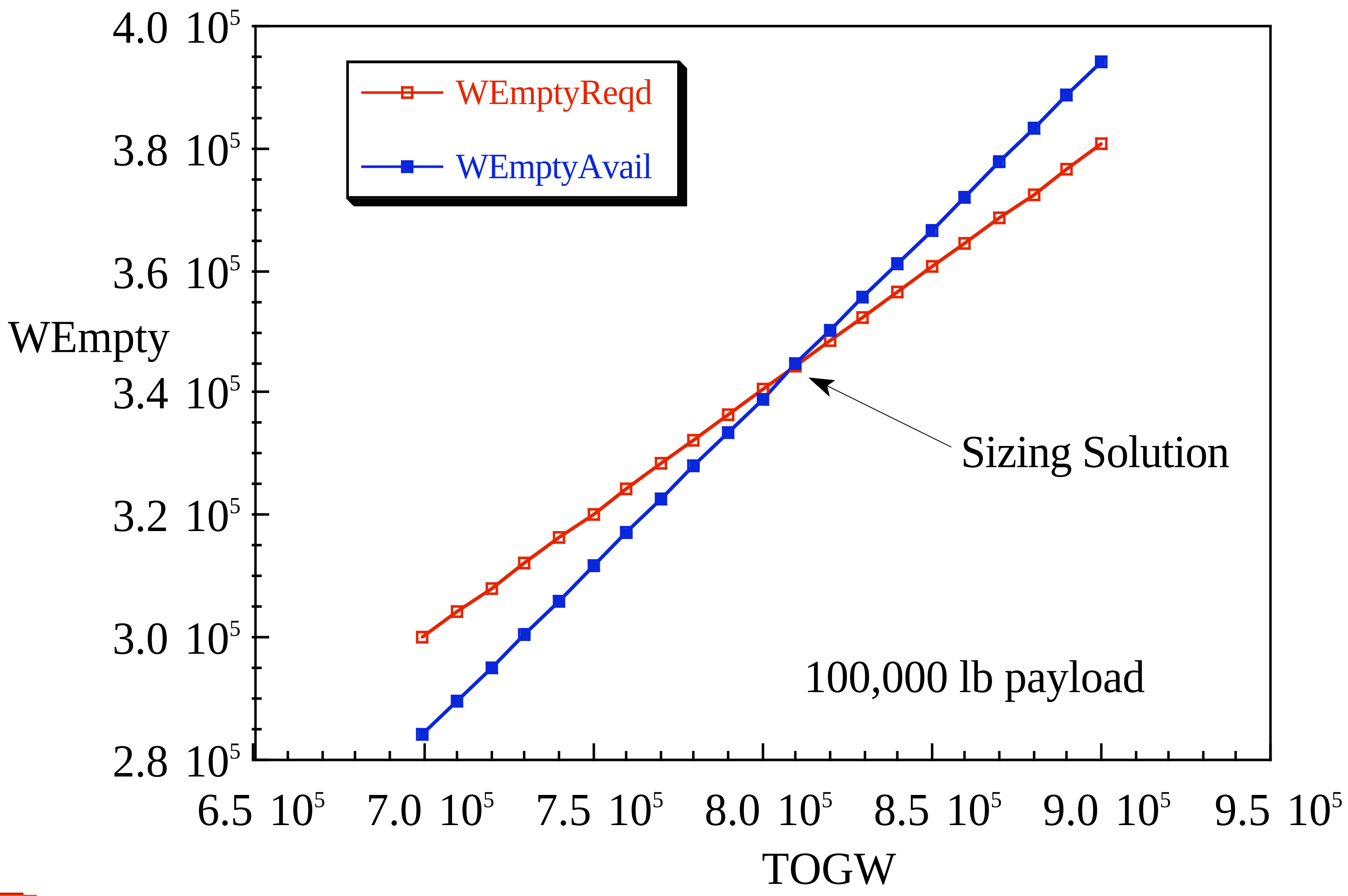


Effect of Range Requirement on Weights for a C-5A Class Aircraft

- all for fixed technology, holding payload constant
- baseline: range = 6000nm
- range = 8000nm: solution obtained
- range = 10,000nm: appears solution would converge (unbelievable weight)
- range = 12,000nm: no solution at any TOGW!

Note: Nicolai, in *Fundamentals of Aircraft Design*, shows that a range-payload diagram which matches the actual C-5A can be developed using our methods.

Range = 6,000 nm case



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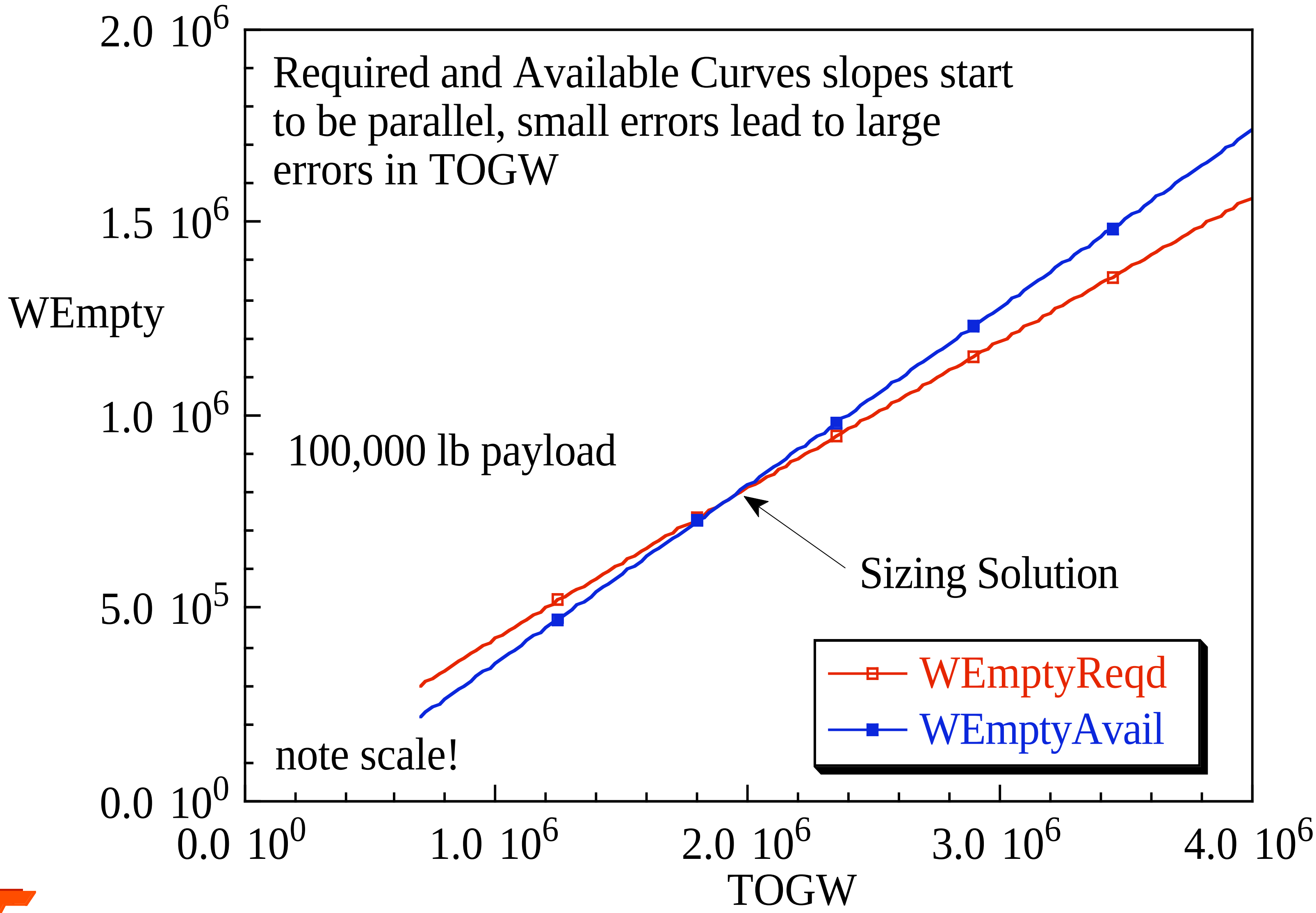
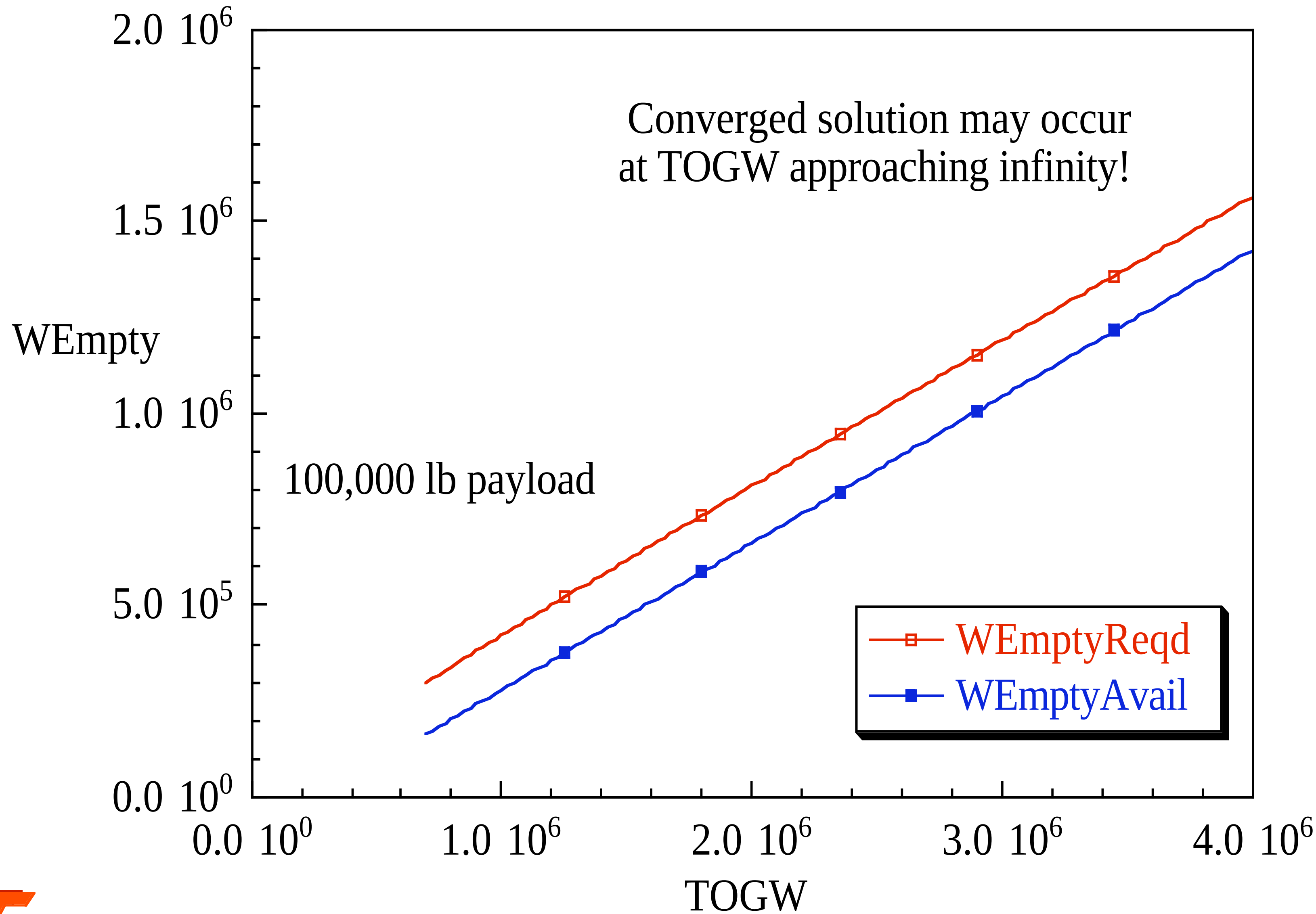
Range = 8,000 nm case



Range = 10,000 nm case



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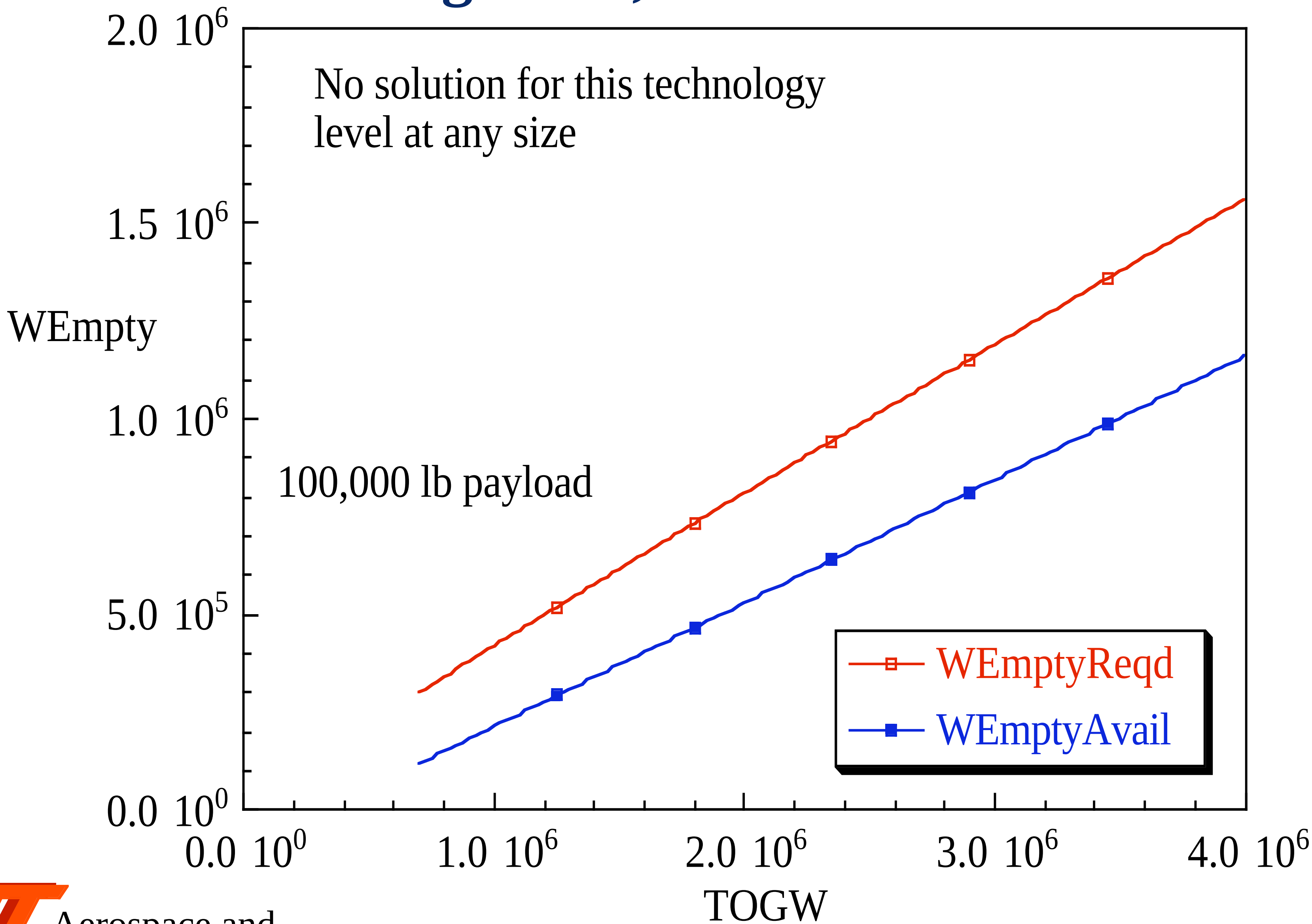
Range = 12,000 nm case



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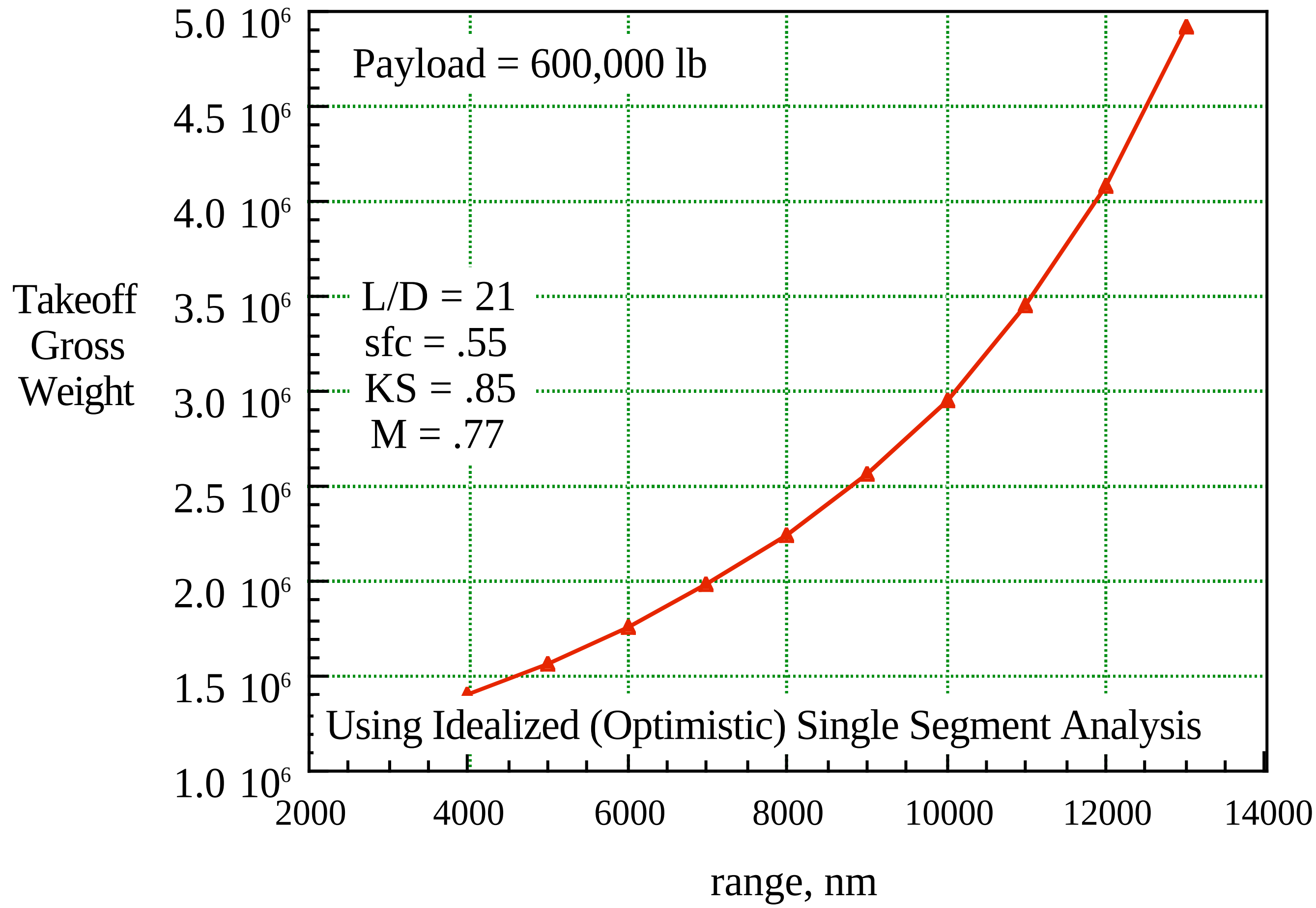
TOGW Weight Growth:

for a specified technology level
the range cannot be increased without limit



Note: this case does not correspond to the technology levels used in the previous charts, which are for something close to a C-5. This example was developed for the 1992-93 AIAA Contest Payload, with advanced technology.

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Parametric studies provide insight

You can investigate how the key technology parameters affect the TOGW for a given mission:

– *L/D*

– *sfc*

– *Ks*

It's worth studying and pondering

To Conclude:

- This method is the 1st cut *back of the envelope* method for sizing: it works.
- Note: The example codes available on the software link on our web page are for *jet* propulsion
- Your skill: Develop confidence by "predicting" the size of existing airplanes
- You will use a sizing program and practice
- Next sizing class will look at sizing a little more deeply for wing and engine size selection.
  - ***Constraints on takeoff and landing, etc. become critically important***