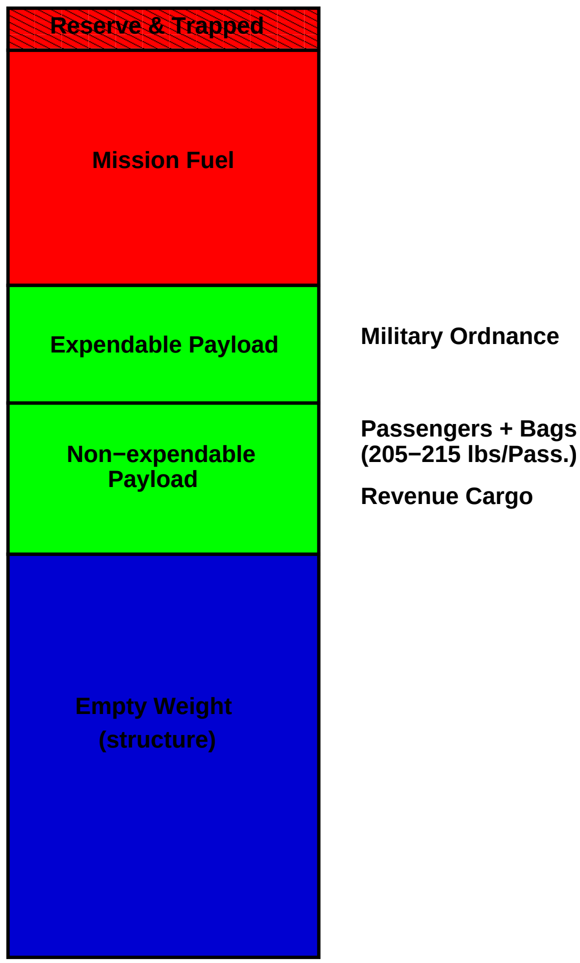
Preliminary Estimate of Take-Off Weight

* Photograph of Boeing C-17 Globemaster at take-off: Maximum take-off weight equals 585,000 lbs, maximum payload is 169,000 lbs (Courtesy of the Boeing Company).

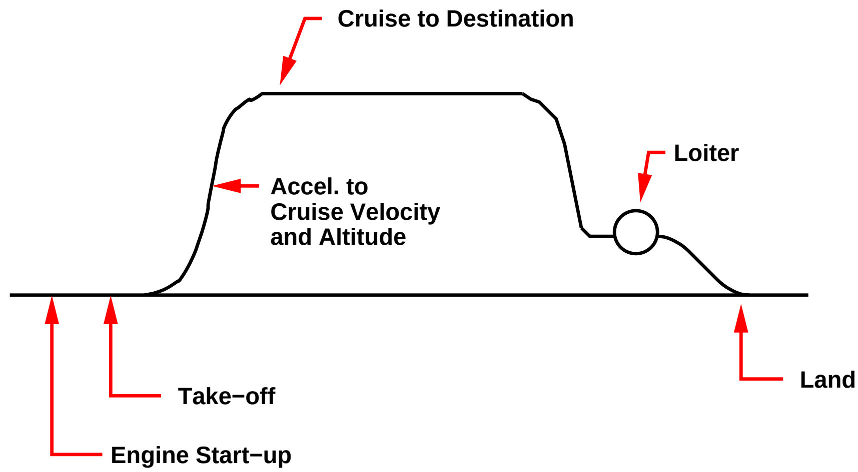
$$W_{TO} = W_{fuel} + W_{payload} + W_{empty}. \quad 2.1$$

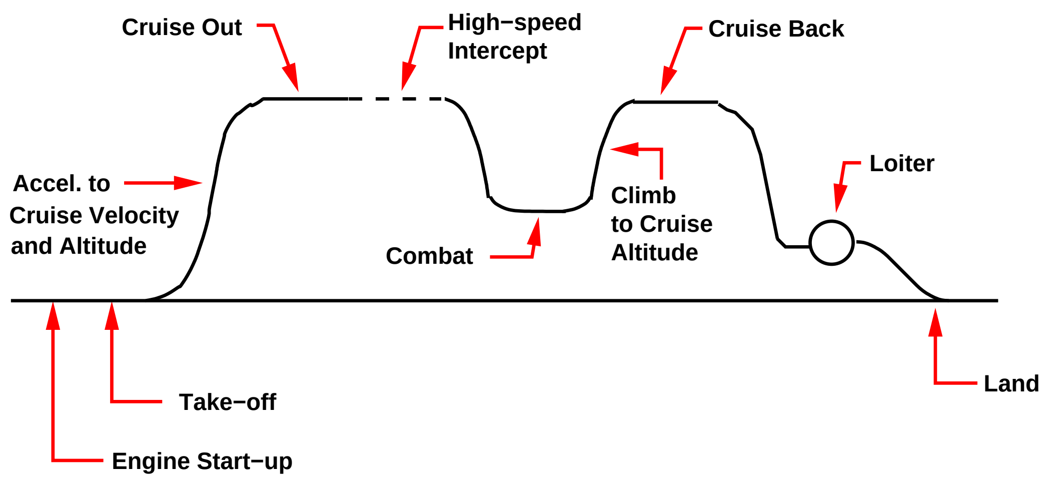
$$W_{payload} = W_{expendable} + W_{non-expendable}. \quad 2.2$$



Weight Buildup

- Fuel weight is based on the flight plan. It considers the fuel used in all of the flight phases:





Fuel Fraction Estimates.

- Total amount of fuel is based on the **sum of individual amounts** used within each flight phase.

$$\text{Fuel Weight Fraction} = (W_f/W_i)_{fuel}. \qquad 2.3$$

$$(W_{landing}/W_{take-off})_{fuel} = \frac{W_2}{W_1}\frac{W_3}{W_2}\cdots\frac{W_N}{W_{N-1}} \qquad 2.4$$

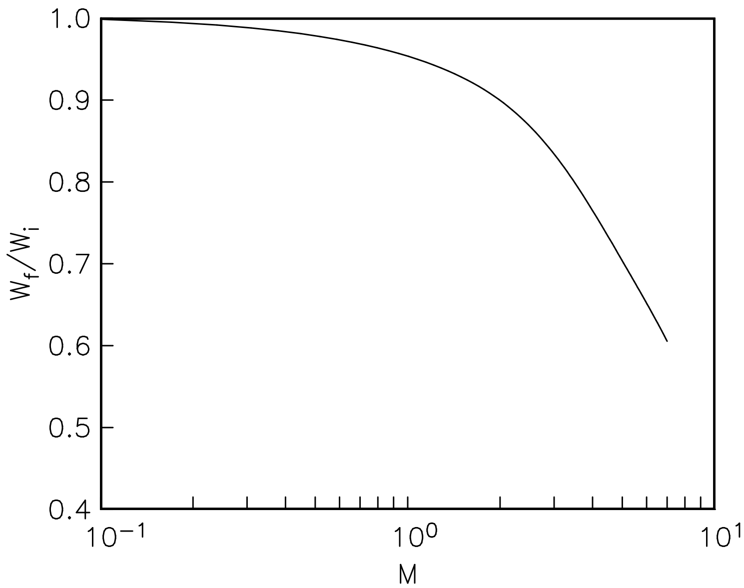
where 1,2,... N represent the individual flight phases in order in the flight plan, starting with take-off (1) and ending with landing (N).

1. Engine start-up and take-off.

- Consists of starting the engines, taxiing to the take-off position, take-off and climb out.
- Empirical estimate:

$$0.97 \leq \frac{W_f}{W_i} \leq 0.975. \qquad 2.5$$

2. Climb and accelerate to cruise conditions.



3. Cruise out to destination.

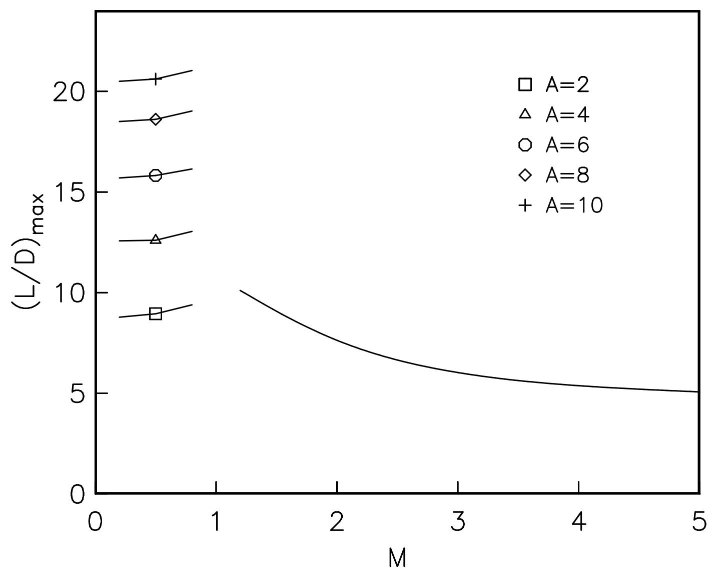
- Based on Brequet range equation.

$$R = \frac{V}{C}\frac{L}{D}\ln\left[\frac{W_i}{W_f}\right] \qquad 2.6a$$

$$R = \frac{\eta}{C}\frac{L}{D}\ln\left[\frac{W_i}{W_f}\right] \qquad 2.6b$$

- NOTE: exponential dependence ⇒ extreme sensitivity to choices
- Start with L/D. A reasonable estimate is

$$\frac{L}{D} = 0.94\left[\frac{L}{D}\right]_{max}. \qquad 2.7$$



- Other historic trends:

	L/D_{max} Range	Average L/D_{max}
Propeller Personal/Utility	9.6 - 14.2	12.1
Propeller Commercial Transport	13.8 - 18.5	16.3
Business Jet	13.0 - 15.6	14.3
Commercial Jet Transport	15.0 - 18.2	14.4
Military Transport/Bomber	17.5 - 20.5	18.9
Military Fighter (subsonic cruise)	9.2 - 13.9	11.0

- For V/C, a general range is

$$0.5 \leq C \leq 1.2 \qquad 2.12$$

- For **propeller driven aircraft**: use Eqs[2.13 - 2.14] and historic trends.

	η	C
Personal/Utility	0.80	0.60
Commuter	0.82	0.55
Regional Turboprop	0.85	0.50

4. Acceleration to high speed (intercept).

- Consider acceleration in two phases:
  1. Acceleration from low speed (Mach 0.1) to cruise Mach number, M_c.
  2. Acceleration from low speed (Mach 0.1) to the maximum Mach number, M_{max}.
- The weight fraction for (1) is

$$\frac{W_f}{W_i} = \frac{W_c}{W_{.1}}. \qquad 2.15$$

- The weight fraction for (2) is

$$\frac{W_f}{W_i} = \frac{W_{max}}{W_{.1}}. \qquad 2.16$$

- The total weight fraction to accelerate from M_c to M_{max} is

$$\frac{W_f}{W_i} = \frac{W_{max}}{W_c} = \frac{W_{max}}{W_{.1}} \left[\frac{W_c}{W_{.1}}\right]^{-1} \qquad 2.17$$

5. Combat.

- Defined as a time, t_{combat}
- Weight of fuel used during during combat is

$$W_i - W_f = C_{max} T_{max} t_{combat}. \tag{2.18}$$

- TAKE CARE with Units!
- If ordnance is dropped, this weight is subtracted during combat.

6. Return cruise.

- Either:

  1. Return to the point of origin to land.

  2. Continue on second half of the cruise phase.

- Treated exactly like cruise out with **two possible exceptions**.

  1. Substantially lower weight $\Rightarrow$ Increase in altitude for same lift.

  2. Substantially lower weight $\Rightarrow$ Maintain altitude with added trim drag (lower L/D).

- Largest effect for long-range aircraft.

7. Loiter.

- Based on Endurance equation.

- Two forms: for turbo-jet and reciprocating engines,

$$E = \frac{1}{C}\frac{L}{D}\ln\left[\frac{W_i}{W_f}\right] \qquad 2.19a$$

$$E = \frac{\eta}{C}\frac{L}{D}\frac{1}{V}\ln\left[\frac{W_i}{W_f}\right] \qquad 2.19b$$

where E is the endurance (loiter) time.

- **Maximum endurance** $\Rightarrow$ maximize $L/(DC)$.
- Initial approximation,

$$\left[\frac{L}{DC}\right]_{max} \simeq \left[\frac{L}{D}\right]_{max}. \qquad 2.20$$

L/D_{max} found as before.

- For propeller driven:

$$E = \frac{T}{P}\frac{L}{DC}\frac{1}{V}\ln\left[\frac{W_i}{W_f}\right]. \qquad 2.21$$

- **Maximum endurance** $\Rightarrow$ shaft power ,P, is a minimum $\Rightarrow$ L/D is a maximum.

8. Landing.

- Emperical like take-off

$$0.97 \le \frac{W_f}{W_i} \le 0.975. \qquad 2.22$$

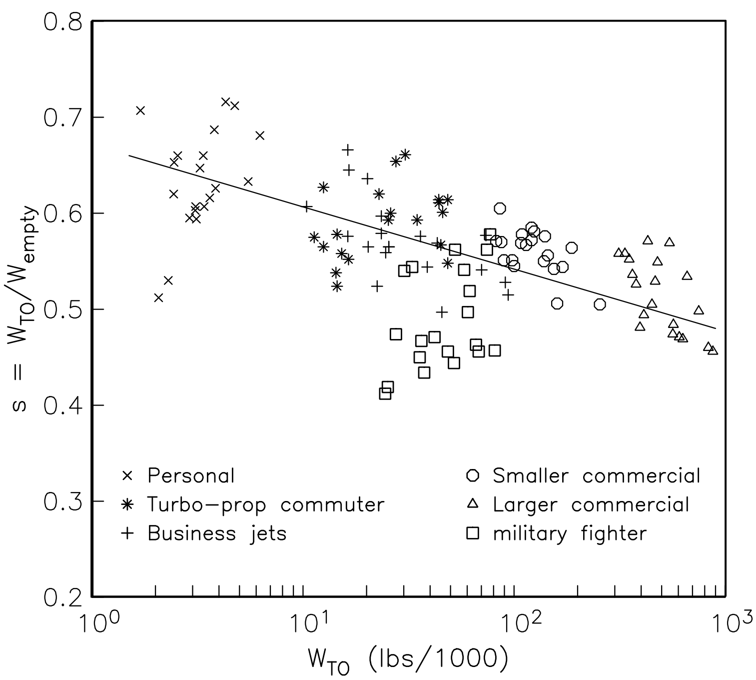
Total take-off weight.

$$(W_{landing}/W_{take-off})_{fuel} = \frac{W_2}{W_1}\frac{W_3}{W_2}\cdots\frac{W_N}{W_{N-1}} \qquad 2.4$$

- Add 5% reserve and 1% trapped fuel.
- The structure weight is determined from the structure coefficient,

$$s = \frac{W_{empty}}{W_{TO}} \qquad 2.23$$

- Historical trends:



$s = AW_{TO}^{C}$	A	C
Sailplane (unpowered)	0.86	-0.05
Sailplane (powered)	0.91	-0.05
Homebuilt (metal/wood)	1.19	-0.09
Homebuilt (composite)	0.99	-0.09
Homebuilt (composite)	0.99	-0.09
General aviation (single engine)	2.36	-0.18
General aviation (twin engine)	1.51	-0.10
Twin turboprop	0.96	-0.05
Jet trainer	1.59	-0.10
Jet fighter	2.34	-0.13
Military cargo/bomber	0.93	-0.07
Jet transport	1.02	-0.06

- The final take-off weight

$$W_{TO} = W_{fuel} + W_{payload} + W_{empty}. \qquad 2.1$$

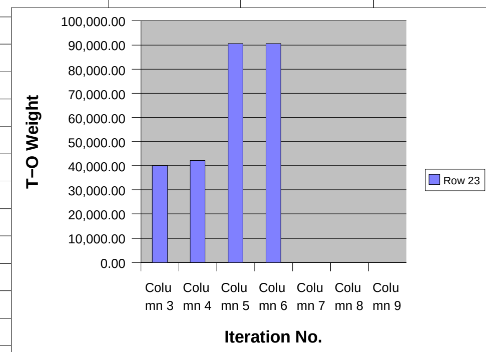
- The difference between the available empty weight and the required empty weight gives the surplus empty weight **which should be zero**.

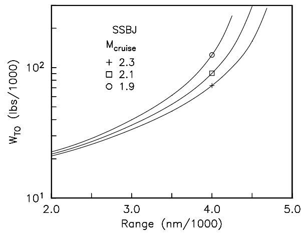
- This requires an **iterative approach** where an initial take-off weight is guessed.

Spread sheet approach for take-off weight estimate.

- **itertow.xls**: "Iter" refers to the fact that the calculations use iterative steps to reach the solution of the take-off weight.

	Mission Requirements				
Max. Mach	2.1				
Cruise Mach	2.1				
Cruise Alt. (ft)	55,000				
Oper. Rad. (nm)	2,000				
Engine: TSFC Min.	0.9				
Engine: TSFC Max.	2.17				
Engine: Thrust (lbs)	108,540				
Aspect Ratio	2				
Combat: Time (min)	0				
Combat: Altitude (ft)	30,000				
Loiter: Time (min)	10				
Loiter: Altitude (ft)	0				
Fuel Reserve (%)	5				
Trapped Fuel (%)	1				
Structure Factor	0.5				
Payload: Exp. (lb)	0				
Payload: Non−exp. (lb)	4000				
		Iteration 1	Iteration 2	Iteration 3	Iteration 4
Weight: T−O (estimated)	40,000	40,000.00	42,232.50	90,523.17	90,523.17
Weight: T−O (final)		42,232.50	44,366.34	90,523.17	90,523.17
Surplus Empty Wt. (lbs)		−2,232.50	−2,133.85	0.00	0.00
1. Start−up & T−O		39,000.00	41,176.68	88,260.09	88,260.09
2. Climb & Accel. to Cruise		36,153.00	38,170.79	81,817.10	81,817.10
3a. L/D		7.59	7.59	7.59	7.59
3b. V (f/s)		1,925.70	1,925.70	1,925.70	1,925.70
3c. Cruise to destination		29,364.58	31,003.49	66,454.38	66,454.38
4. Accel. to high speed		29,364.58	31,003.49	66,454.38	66,454.38
5. Combat		29,364.58	31,003.49	66,454.38	66,454.38
6. Drop Exp. Payload		29,364.58	31,003.49	66,454.38	66,454.38
7. Cruise back		23,850.82	25,182.00	53,976.30	53,976.30
7. Loiter		23,384.13	24,689.26	52,920.15	52,920.15
8. Land		22,799.53	24,072.03	51,597.15	51,597.15
Total Fuel Wt. (lbs)		18,232.50	19,250.10	41,261.58	41,261.58
Available Empty Wt. (lbs)		17,767.50	18,982.40	45,261.58	45,261.58
Required Empty Wt. (lbs)		20,000.00	21,116.25	45,261.58	45,261.58





SSBJ
M_{cruise}
+ 2.3
□ 2.1
○ 1.9
W_{TO} (lbs/1000)
10^2
10^1
2.0
3.0
4.0
5.0
Range (nm/1000)