MODULE I -OVERVIEW OF DESIGN PROCESS

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MODULE I
OVERVIEW OF DESIGN PROCESS

1.1- WHAT IS DESIGN

- Aircraft design is a separate discipline of aeronautical engineering different from the analytical disciplines such as aerodynamics, structures, controls, and propulsion. An aircraft designer needs to be well versed in these and many other specialties, but will actually spend little time performing such analysis in all but the smallest companies. Instead, the designer's time is spent doing something called "design," creating the geometric description of a thing to be built.

- To the uninitiated, "design" looks a lot like "drafting" (or in the modern world, "computer-aided drafting"). The designer's product is a drawing, and the designer spends the day hunched over a drafting table or computer terminal.

- A good aircraft design seems to miraculously glide through subsequent evaluations by specialists without major changes being required. Somehow, the landing gear fits, the fuel tanks are near the center of gravity, the structural members are simple and lightweight, the overall arrangement provides good aerodynamics, the engines install in a simple and clean fashion, and a host of similar detail seems to fall into place.

- Design is not just the actual layout, but also the analytical processes used to determine what should be designed and how the design should be modified to better meet the requirements. In the larger companies, aircraft analysis is done by the sizing and performance specialists with the assistance of experts in aerodynamics, weights, propulsion, stability, and other technical specialties.

1.2- OVERVIEW OF THE DESIGN PROCESS

- Those involved in design can never quite agree as to just where the design process begins. The designer thinks it starts with a new airplane concept. The sizing specialist knows that nothing can begin until an initial estimate of the weight is made. The customer, civilian or military, feels that the design begins with requirements.

- Design is an iterative effort, as shown in the "Design Wheel" of Fig. 1.1. Requirements are set by prior design trade studies. Concepts are developed to meet requirements. Design analysis frequently points toward new concepts and technologies, which can initiate a whole new design effort. However, a particular design is begun, all of these activities are equally important in producing a good aircraft concept.

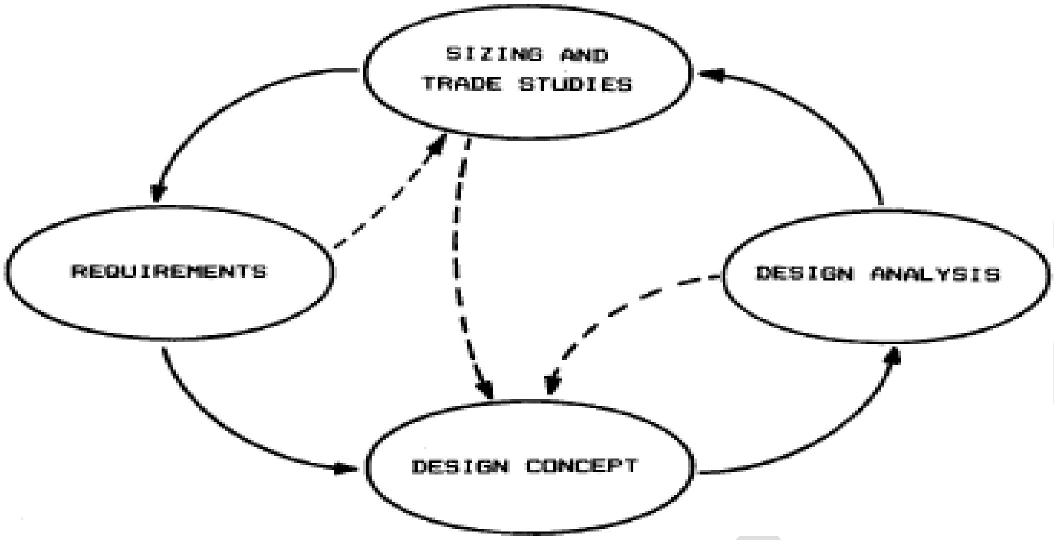

FIG: 1.1 - The Design Wheel

1.3- PHASES OF AIRCRAFT DEISGN

Aircraft design can be broken into three major phases, as (a) conceptual design (b) preliminary design and (c) detail design

(a) Conceptual Design

- Conceptual design is the primary focus. It is in conceptual design that the basic questions of configuration arrangement size and weight, and performance are answered. 'Conceptual design is a very fluid process. New ideas and problems emerge as a design is investigated in ever- increasing detail. Each time the latest design is analyzed and sized, it must be redrawn to reflect the new gross weight, fuel weight, wing size, engine size, and other changes. Early Wind tunnel tests often reveal problems requiring some changes to the configuration. The steps of conceptual design are described later in more detail

(b) Preliminary Design

- This stage of design process aims at producing a brochure containing preliminary drawings and stating the estimated operational capabilities of the airplane. This is used for seeking approval of the manufacturer or the customer. This stage includes the following steps.
  - (i) Preliminary weight estimate.
  - (ii) Selection of geometrical parameters of main components based on design criteria.
  - (iii) Selection of power plant.
  - (iv) Arrangement of equipment, and control systems.
  - (v) Aerodynamic and stability calculations.
  - (vi) Preliminary structural design of main components.

(vii) Revised weight estimation and c.g. travel.
(viii) Preparation of 3-view drawing.
(ix) Performance estimation.
(x) Preparation of brochure.

- After the preliminary design has been approved by the manufacturer / customer. The detailed design studies are carried out. These include the following stages

  - Wind tunnel and structural testing on models of airplane configuration arrived after preliminary design stage. These tests serve as a check on the correctness of the estimated characteristics and assessment of the new concepts proposed in the design.
  - Mock-up: This is a full-scale model of the airplane or its important sections. This helps in
    - Efficient lay-out of structural components and equipment.
    - Checking the clearances, firing angles of guns, visibility etc. Currently this stage is avoided by the use of CAD (Computer Aided Design) packages which provide detailed drawings of various components and subassemblies.
  - Complete wind tunnel testing of the approved configuration. Currently CFD (Computational Fluid Dynamics) plays an important role in reducing the number of tests to be carried-out. In CFD, the equations governing the fluid flow are solved numerically. The results provide flow patterns, drag coefficient, lift coefficient, moment coefficient, pressure distribution etc. Through the results may not be very accurate at high angles of attack, they are generally accurate near the design point. Further, they provide information on the effects of small changes in the geometric parameters, on the flow field and permit parametric studies.
  - Preparation of detailed drawings.
  - Final selection of power plant.
  - Calculations of (a) c.g. shift (b) performance and (c) stability
  - Fabrication of prototypes. These are the first batch of full scale airplane. Generally six prototypes are constructed. Some of them are used for verifying structural integrity and functioning of various systems. Others are used for flight testing to evaluate performance and stability.

(c) Detail Design

- Assuming a favorable decision for entering full-scale development, the detail design phase begins in which the actual pieces to be fabricated are designed. For example, during conceptual and preliminary design the wing box will be designed and analyzed as a whole. During detail design, that whole will be broken down into individual ribs, spars, and skins, each of which must be separately designed and analyzed.

- Another important part of detail design is called production design. Specialists determine how the airplane will be fabricated, starting with the smallest and simplest subassemblies and building up to the final assembly process. Production designers frequently wish to modify the design for ease of manufacture; that can have a major impact on performance or weight. Compromises are inevitable, but the design must still meet the original requirements.
- During detail design, the testing effort intensifies. Actual structure of the aircraft is fabricated and tested. Control laws for the flight control system are tested on an "iron-bird" simulator, a detailed working model of the actuators and flight control surfaces. Flight simulators are developed and flown by both company and customer test-pilots.
- Detail design ends with fabrication of the aircraft. Frequently the fabrication begins on part of the aircraft before the entire detail-design effort is completed. Hopefully, changes to already- fabricated pieces can be avoided.

1.4- AIRCRAFT CONCEPTUAL DESIGN PROCESS

- Conceptual design will usually begin with either a specific set of design requirements established by the prospective customer or a company-generated guess as to what future customers may need. Design requirements include parameters such as the aircraft range and payload, takeoff and landing distances, and manoeuvrability and speed requirements.

- The design requirements also include a vast set of civil or military design specifications which must be met. These include landing sink-speed, stall speed, structural design limits, pilots' outside vision angles, reserve fuel, and many others. Sometimes a design will begin as an innovative idea rather than as a response to a given requirement

- Before a design can be started, a decision must be made as to what technologies will be incorporated. If a design is to be built in the near future, it must use only currently-available technologies as well as existing engines and avionics. If it is being designed to be built in the more distant future, then an estimate of the technological state of the art must be made to determine which emerging technologies will be ready for use at that time.
- An optimistic estimate of the technology availability will yield a lighter, cheaper aircraft to perform a given mission, but will also result in a higher development risk. The actual design effort usually begins with a conceptual sketch

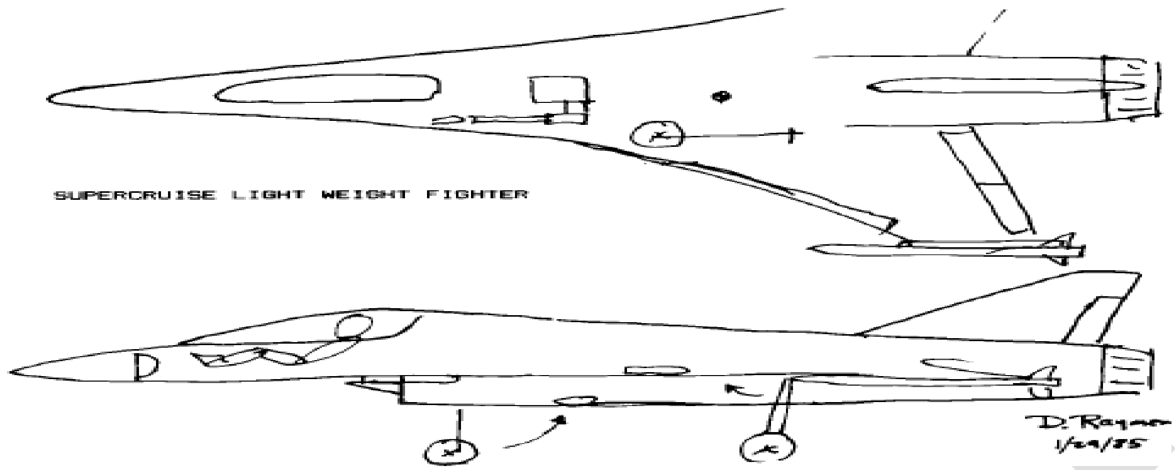

FIG: 1.2- Initial Sketch

- This is the "back of a napkin" drawing of aerospace legend, and gives a rough indication of what the design may look like. A good conceptual sketch will include the approximate wing and tail geometries, the fuselage shape, and the internal locations of the major components such as the engine, cockpit, payload/passenger compartment, landing gear, and perhaps the fuel tanks. The conceptual sketch can be used to estimate aerodynamics and weight fractions by comparison to previous designs. These estimates are used to make a first estimate of the required total weight and fuel weight to perform the design mission, by a process called "sizing."

- The conceptual sketch may not be needed for initial sizing if the design resembles previous ones. The "first-order" sizing provides the information needed to develop an initial design layout

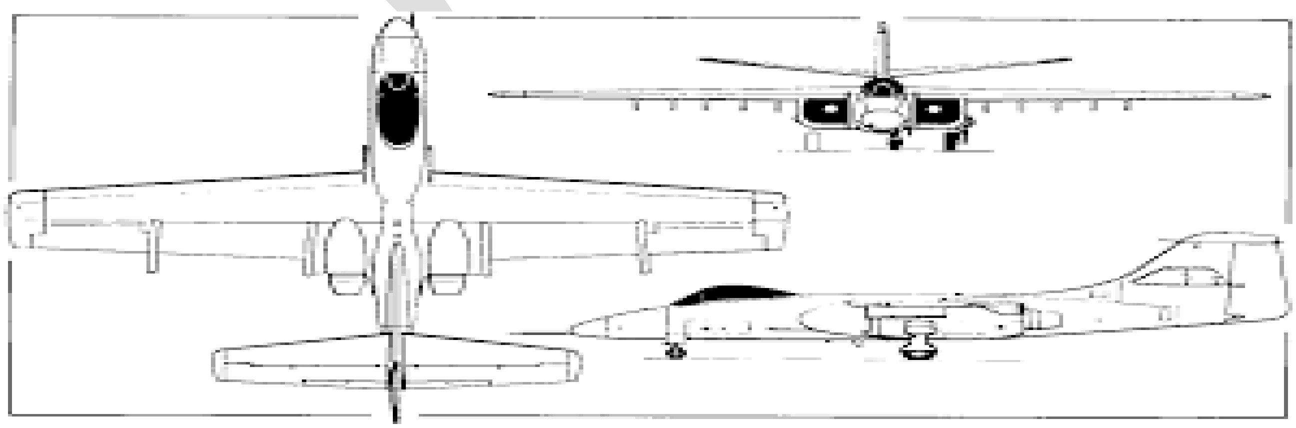

FIG – 1.3- Configuration Layout

- This is a three-view drawing complete with the more important internal arrangement details, including typically the landing gear, payload or passenger compartment, engines and inlet ducts, fuel tanks, cockpit, major avionics, and any other internal components which are large enough to affect the overall shaping of the aircraft. Enough cross-sections are shown to verify that everything fits.

- On a drafting table, the three-view layout is done in some convenient scale such as 1/10, 1/20, 1/40, or 1/100 (depending upon the size of the airplane and the available paper). On a computer-aided design system, the design work is usually done in full scale (numerically).

- This initial layout is analyzed to determine if it really will perform the mission as indicated by the first-order sizing. Actual aerodynamics, weights, and installed propulsion characteristics are analyzed and subsequently used to do a detailed sizing calculation. Furthermore, the performance capabilities of the design are calculated and compared to the requirements mentioned above. Optimization techniques are used to find the lightest or lowest-cost aircraft that will both perform the design mission and meet all performance requirements.

- The results of this optimization include a better estimate of the required total weight and fuel weight to meet the mission. The results also include required revisions to the engine and wing sizes. This frequently requires a new or revised design layout, in which the designer incorporates these changes and any others suggested by the effort to date. The revised drawing, after some number of iterations, is then examined in detail by an ever-expanding group of specialists, each of whom insures that the design meets the requirements of that specialty

- The end product of all this will be an aircraft design that can be confidently passed to the preliminary design phase, as previously discussed. While further changes should be expected during preliminary design, major revisions will not occur if the conceptual design effort has been successful.

1.5- SIZING FROM A CONCEPTUAL SKETCH

- There are many levels of design procedure. The simplest level just adopts past history. For example, if you need an immediate estimate of the takeoff weight of an airplane to replace the Air Force F-15 fighter, use 44,500 lb. That is what the F-15 weighs, and is probably a good number to start with.

- To get the "right" answer takes several years, many people, and lots of money. Actual design requirements must be evaluated against a number of candidate designs, each of which must be designed, analyzed, sized, optimized, and redesigned any number of times. Analysis techniques include all manner of computer code as well as correlations to wind-tunnel and other tests. Even with this extreme level of design sophistication, the actual airplane when flown will never exactly match predictions.

- The simplified sizing method presented in this section can only be used for missions which do not include any combat or payload drops. While admittedly crude, this method introduces all of the essential features of the most sophisticated design by the major aerospace manufacturers.

1.6- TAKE OFF WEIGHT BUILD UP

- "Design takeoff gross weight" is the total weight of the aircraft as it begins the mission for which it was designed. This is not necessarily the same as the "maximum takeoff weight." Many military aircraft can be overloaded beyond design weight but will suffer a reduced manoeuvrability. Unless specifically mentioned, takeoff gross weight, or *"W0,"* is assumed to be the design weight. Design takeoff gross weight can be broken into crew weight, payload (or passenger) weight, fuel weight, and the remaining (or "empty") weight. The empty weight includes the structure, engines, landing gear, fixed equipment, avionics, and anything else not considered a part of crew, payload, or fuel.

- Equation (1.1) summarizes the takeoff-weight build-up.

$$W_0 = W_{crew} + W_{payload} + W_{fuel} + W_{empty} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_ (1.1)}$$

- The crew and payload weights are both known since they are given in the design requirements. The only unknowns are the fuel weight and empty weight. However, they are both dependent on the total aircraft weight.
- Thus an iterative process must be used for aircraft sizing.

- To simplify the calculation, both fuel and empty weights can be expressed as fractions of the total takeoff weight, i.e., *(Wj/Wo)* and *(We/Wo)*

- Thus equation (1.1) becomes

$$W_0 = W_{crew} + W_{payload} + \left(\frac{W_f}{W_0}\right)W_0 + \left(\frac{W_e}{W_0}\right)W_0 \qquad \text{-\_\_\_\_\_\_\_\_\_ (1.2)}$$

This can be solved for *W0* as follows:

$$W_0 - \left(\frac{W_f}{W_0}\right) W_0 - \left(\frac{W_e}{W_0}\right) W_0 = W_{crew} + W_{payload}$$ -________ (1.3)

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - (W_f/W_0) - (W_e/W_0)}$$ _____(1.4)

Now *Wo* can be determined if *(Wf/Wo)* and *(We/Wo)* can be estimated. These are described below.

1.7- EMPTY WEIGHT FRACTION

- The empty-weight fraction *(We/* Wo) can be estimated statistically from historical trends as shown in Fig1. 4. Empty-weight fractions vary from about 0.3 to 0.7, and diminish with increasing total aircraft weight. As can be seen, the type of aircraft also has a strong effect, with flying boats having the highest empty-weight fractions and long-range military aircraft having the lowest. Flying boats are heavy because they need to carry extra weight for what amounts to a boat hull. Notice also that different types of aircraft exhibit different slopes to the trend lines of empty-weight Fraction vs. takeoff weight.

- Table 1.1 presents statistical curve-fit equations for the trends shown in fig 1.4. Note that these are all exponential equations based upon takeoff gross weight. The exponents are small negative numbers, which indicates that the empty weight fractions decrease with increasing takeoff weight, as shown by the trend lines in fig 1.4. The differences in exponents for different types of aircraft reflect the different slopes to the trend lines, and imply that some types of aircraft are more sensitive in sizing than others.

- A variable-sweep wing is heavier than a fixed wing, and is accounted for at this initial stage of design by multiplying the empty-weight fraction as determined from the equations in Table 1.1 by about 1.04.

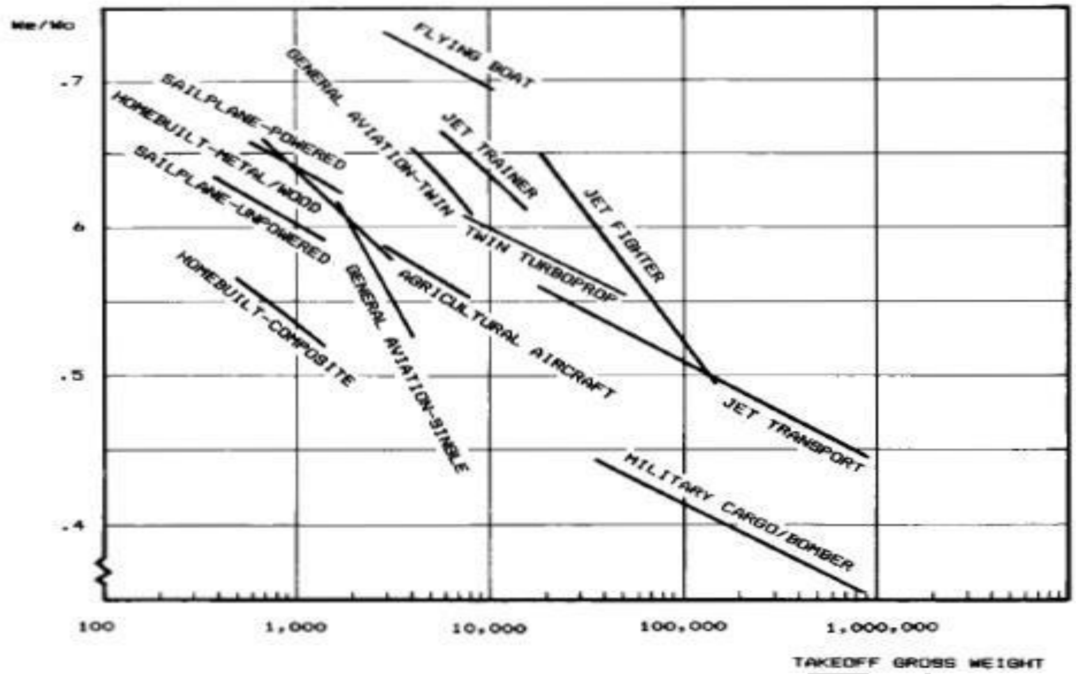

FIG 1.4– Empty Weight Fraction Trends

$W_e/W_0 = A W_0^C K_{vs}$	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
General aviation—single engine	2.36	−0.18
General aviation—twin engine	1.51	−0.10
Agricultural aircraft	0.74	−0.03
Twin turboprop	0.96	−0.05
Flying boat	1.09	−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

K_{vs} = variable sweep constant = 1.04 if variable sweep
= 1.00 if fixed sweep

TABLE 1.1- EMPTY WEIGHT FRACTION VS W0

1.8- FUEL - FRACTION ESTIMATION

- Only part of the aircraft's fuel supply is available for performing the mission ("mission fuel"). The other fuel includes reserve fuel as required by civil or military design specifications, and also includes "trapped fuel," which is the fuel which cannot be pumped out of the tanks. The required amount of mission fuel depends upon the mission to be flown, the aerodynamics of the aircraft, and the engine's fuel consumption. The aircraft weight during the mission affects the drag, so the fuel used is a function of the aircraft weight.

- As a first approximation, the fuel used can be considered to be proportional to the aircraft weight, so the fuel fraction (W_f/W_o) is approximately independent of aircraft weight. Fuel fraction can be estimated based on the mission to be flown using approximations of the fuel consumption and aerodynamics.

1.9- MISSION PROFILES

- Typical mission profiles for various types of aircraft are shown in Fig. 1.5. The Simple Cruise mission is used for many transport and general aviation designs, including homebuilt. The aircraft is sized to provide some required cruise range.

- For safety you would be wise to carry extra fuel in case your intended airport is closed, so a loiter of typically 20-30 min is added. Alternatively, additional range could be included, representing the distance to the nearest other airport or some fixed number of minutes of flight at cruise speed (the FAA requires 30 min of additional cruise fuel for general-aviation aircraft).

- Other missions are more complex. The typical Air Superiority mission includes a cruise out, a combat consisting of either a certain number of turns or a certain number of minutes at maximum power, a weapons drop, a cruise back, and a loiter. The weapons drop refers to the firing of gun and missiles, and is often left out of the sizing analysis to insure that the aircraft
has enough fuel to return safely if the weapons aren't used. Note that the second cruise segment is identical to the first, indicating that the aircraft must return to its base at the end of the mission.

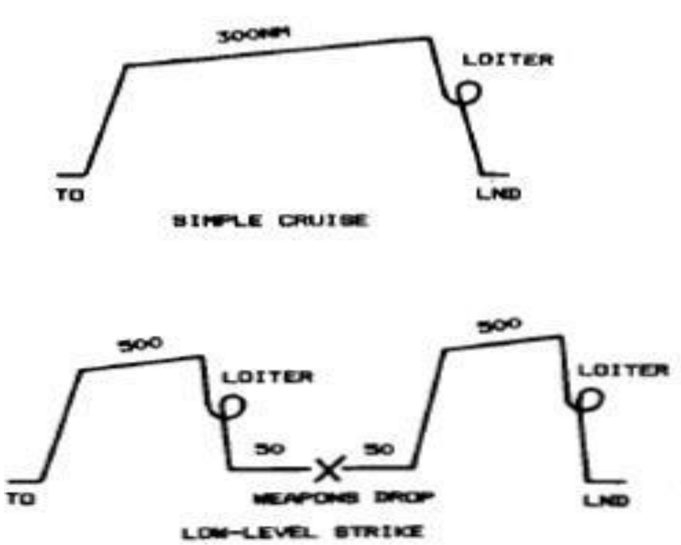

FIG: 1.5- Typical Mission Profiles For Sizing

- The Low-Level Strike mission includes "dash" segments that must be flown at just a few hundred feet off the ground. This is to improve the survivability of the aircraft as it approaches its target. Unfortunately, the aerodynamic efficiency of an aircraft, expressed as "lift-to-drag ratio"*(LID)*, is greatly reduced during low-level, high-speed flight, as is the engine efficiency. The aircraft may burn almost as much fuel during the low-level dash segment as it burns in the much-longer cruise segment.

- The Strategic Bombing mission introduces another twist. After the initial cruise, a refuelling segment occurs, as indicated by an *"R."* Here the aircraft meets up with a tanker aircraft such as an Air Force KC-135 and receives some quantity of fuel. This enables the bomber to achieve far more range, but adds to the overall operating cost because a fleet of tanker aircraft must be dedicated to supporting the bombers.

- Another difference in this strategic mission is the fact that the return cruise range is far shorter than the outbound range. This is necessary because of the extreme range required. If the aircraft were sized to return to its original base, it would probably weigh several million pounds. Instead, it is assumed that strategic bombers will land on bases in friendly countries for refuelling after completion of their mission.

1.10- MISSION SEGMENT WEIGHT FRACTIONS

- For analysis, the various mission segments, or "legs," are numbered, with zero denoting the start of the mission. Mission leg "one" is usually engine warm-up and takeoff for first-order sizing estimation. The remaining legs are sequentially numbered.

For example, in the simple cruise mission the legs could be numbered as
(1) Warm-up and takeoff, (2) climb, (3) cruise, (4) loiter, and (5) land

➢ In a similar fashion, the aircraft weight at each part of the mission can be numbered. Thus, Wo is the beginning weight ("takeoff gross weight").

➢ For the simple cruise mission, W_1 would be the weight at the end of the first mission segment, which is the warm-up and takeoff. W_2 would be the aircraft weight at the end of the climb. W_3 *would* be the weight after cruise, and W_4 after loiter. Finally, W_5 would be the weight at the end of the landing segment, which is also the end of the total mission.

➢ During each mission segment, the aircraft loses weight by burning fuel (remember that our simple sizing method doesn't permit missions involving a payload drop). The aircraft weight at the end of a mission segment divided by its weight at the beginning of that segment is called the "mission segment weight fraction." This will be the basis for estimating the required fuel fraction for initial sizing.

- For any mission segment " *i*," the mission segment weight fraction can be expressed as $(W_i/W = 1)$. If these weight fractions can be estimated for all of the mission legs, they can be multiplied together to find the ratio of the aircraft weight at the end of the total mission, *Wx* (assuming "*x*" segments altogether) divided by the initial weight, *W0*• This ratio, *WxlW0*, can then be used to calculate the total fuel fraction required.
- These mission segment weight fractions can be estimated by a variety of methods. For our simplified form of initial sizing, the types of mission leg will be limited to warm-up and takeoff, climb, cruise, loiter, and land.
- The warm up, takeoff, and landing weight-fractions can be estimated historically. Table gives typical historical values for initial sizing. These values can vary somewhat depending on aircraft type, but the averaged values given in the table are reasonable for initial sizing.

	(W_i/W_{i-1})
Warmup and takeoff	0.970
Climb	0.985
Landing	0.995

TABLE: 1.2- Historical Mission Segment Weight Fractions

- In our simple sizing method descent is ignored, assuming that the cruise ends with a descent and that the distance travelled during descent is part of the cruise range.
- Cruise-segment mission weight fractions can be found using the Breguet range equation

$$R = \frac{V}{C}\frac{L}{D}\ln\frac{W_{i-1}}{W_i} \qquad (1)$$

Or

$$\frac{W_i}{W_{i-1}} = \exp\frac{-RC}{V(L/D)} \qquad (2)$$

Where
R =range
C = specific fuel consumption
V =velocity
LID = lift-to-drag ratio

Loiter weight fractions are found from the endurance equation

$$E = \frac{L/D}{C} \ln \frac{W_{i-1}}{W_i}$$ --------------------------

Or

$$\frac{W_i}{W_{i-1}} = \exp \frac{-EC}{L/D}$$ --------------------------(4)

Where *E* = endurance or loiter time.

1.11- SPECIFIC FUEL CONSUMPTION

Specific fuel consumption ("SFC" or simply "C") is the rate of fuel consumption divided by the resulting thrust. For jet engines, specific fuel consumption is usually measured in pounds of fuel per hour per pound of thrust [(lb/hr)/lb, or 1/hr]. Figure 1.7 shows SFC vs Mach number.

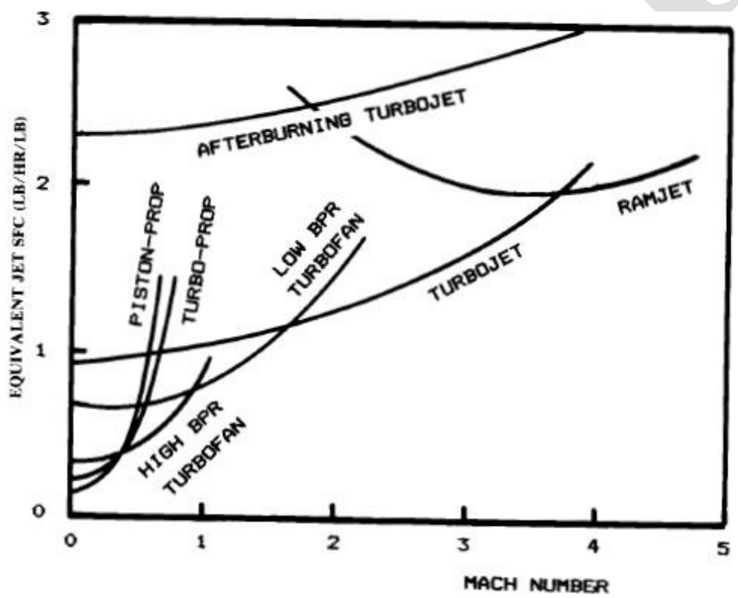

FIG -1.6–Specific Fuel Consumption trends

- Propeller engine SFC is normally given as Cbhp, the pounds of fuel per hour to produce one horsepower at the propeller shaft (or one "brake horsepower": bhp = 550 ft-Ibis).A propeller thrust SFC equivalent to the jet-engine SFC can be calculated.

- The engine produces thrust via the propeller, which has an efficiency ηp defined as thrust power output per horsepower input the *550* term assumes that *V is* in feet per second.

$$\eta_p = \frac{TV}{550 \text{ hp}}$$

_________*(1)*

- Equation 2 shows the derivation of the equivalent-thrust SFC for a propeller-driven aircraft. Note that for a propeller aircraft the thrust and the SFC are a function of the flight velocity. For a typical aircraft with a propeller efficiency of about 0.8, one horsepower equals one pound of thrust at about 440 ft/s, or about 260 knots.

$$C = \frac{W_f/\text{time}}{\text{thrust}} = C_{\text{bhp}} \frac{V}{550\,\eta_p}$$

____________(2)

Table- 1.3 provides typical SFC values for jet engines, while Table –1.4 provides typical Cbhp and *ηp* values for propeller engines. These can be used for rough initial sizing.

TABLE: 1.3: Specific Fuel Consumption (C)

Propeller: $C = C_{\text{bhp}} V/(550\eta_p)$ Typical C_{bhp} and η_p	Cruise	Loiter
Piston-prop (fixed pitch)	0.4/0.8	0.5/0.7
Piston-prop (variable pitch)	0.4/0.8	0.5/0.8
Turboprop	0.5/0.8	0.6/0.8

TABLE: 1.4: Propeller Specific Fuel Consumption (Cbhp)

1.12- FUEL FRACTION ESTIMATION

Using historical values from Table –1.3 and the equations for cruise and loiter segments, the mission-segment weight fractions can now be estimated. By multiplying them together, the total mission weight fraction, *WxlWo,* can be calculated. Since this simplified sizing method does not allow mission segments involving payload drops, all weight lost during the mission must be due to fuel usage. The mission fuel fraction must therefore be equal to (1 - *WxlWo)*. If you assume, typically, a 6% allowance for reserve and trapped fuel, the total fuel fraction can be estimated as in Eq. below

$$\frac{W_f}{W_0} = 1.06\left(1 - \frac{W_x}{W_0}\right)$$

__________**(1)**

1.13- TAKE OFF WEIGHT CALCULATION

Using the fuel fraction found with Eq. (1) above and the statistical empty weight equation selected from Table (Empty weight fraction vs. W0), the takeoff gross weight can be found iteratively from Eq.W0= Wcrew + Wpayload/ 1 - *(Wf/Wo)* -*(We/Wo)*).

This is done by guessing the takeoff gross weight, calculating the statistical empty-weight fraction, and then calculating the takeoff gross weight. If the result doesn't match the guess value, a value between the two is used as the next guess. This will usually converge in just a few iterations. This first-order sizing process is diagrammed in fig 1.8.

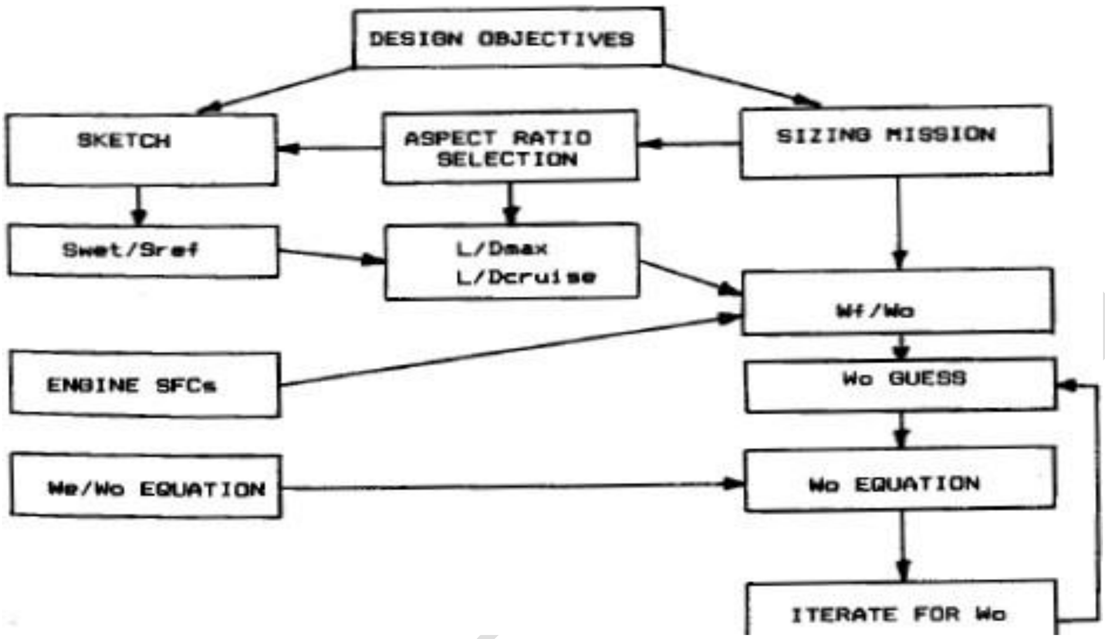

FIG: 1.7- First-Order Design Method.

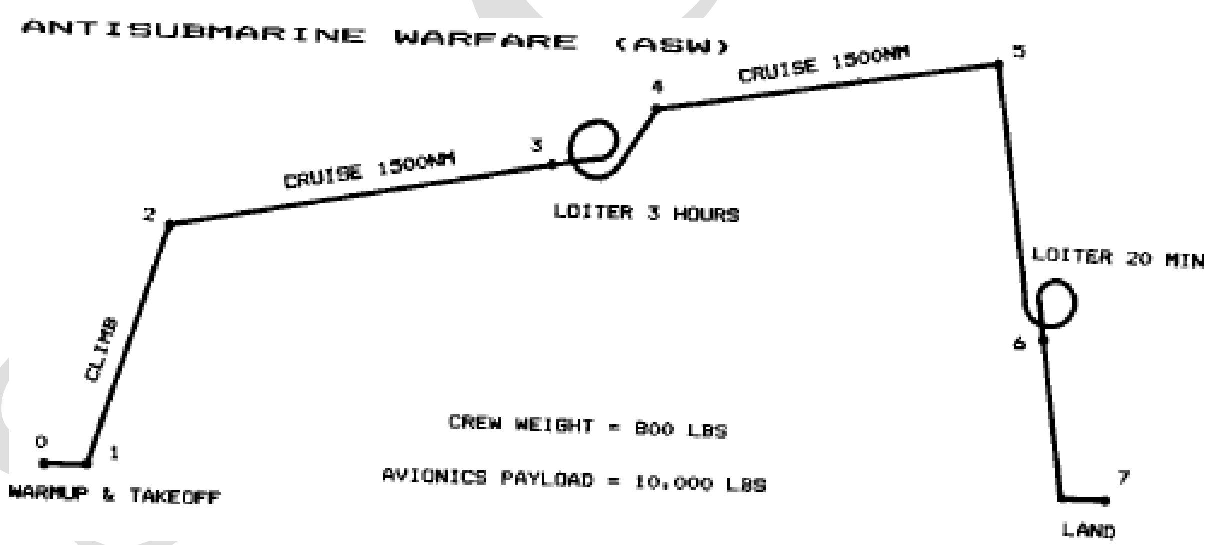

FIG: 1.8 – Sample Mission Profile

MODULE I
THRUST TO WEIGHT RATIO AND WING LOADING

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MODULE I
THRUST TO WEIGHT RATIO AND WING LOADING

The thrust-to-weight ratio *(T/W)* and the wing loading *(W/S)* are the two most important parameters affecting aircraft performance. Optimization of these parameters forms a major part of the analytical design activities conducted after an initial design layout.

- However, it is essential that a credible estimate of the wing loading and thrust-to-weight ratio be made before the initial design layout is begun. Otherwise, the optimized aircraft may be so unlike the as-drawn aircraft that the design must be completely redone

- Wing loading and thrust-to-weight ratio are interconnected for a number of performance calculations, such as takeoff distance, which is frequently a critical design driver. A requirement for short takeoff can be met by using a large wing (low *WIS)* with a relatively small engine (low *T/W)*. While the small engine will cause the aircraft to accelerate slowly, it only needs to reach a moderate speed to lift off the ground.

- On the other hand, the same takeoff distance could be met with a small wing (high *W/S)* provided that a large engine (high *T/W)* is also used. In this case, the aircraft must reach a high speed to lift off, but the large engine can rapidly accelerate the aircraft to that speed.

1.17- THRUST TO WEIGHT RATIO

THRUST TO WEIGHT

DEFINITIONS

- *T/W* directly affects the performance of the aircraft. An aircraft with a higher *T/W will* accelerate more quickly, climb more rapidly, reach a higher maximum speed, and sustain higher turn rates. On the other hand, the larger engines will consume more fuel throughout the mission, which will drive up the aircraft's takeoff gross weight to perform the design mission.

- *T/*W is not a constant. The weight of the aircraft varies during flight as fuel is burned. Also, the engine's thrust varies with altitude and velocity (as does the horsepower and propeller efficiency, η_P).

- When designers speak of an aircraft's thrust-to-weight ratio they generally refer to the *T/W* during sea-level static (zero-velocity), standard-day conditions at design takeoff weight and maximum throttle setting. Another commonly referred-to *T/W* concems combat conditions.

- *T/W* can also be calculated at a partial-power setting. For example, during the approach to landing the throttle setting is near idle. The operating *T/W* at that point in the mission is probably less than 0.05.

1.18- POWER LOADING AND HORSEPOWER-TO-WEIGHT

- The term "thrust-to-weight" is associated with jet-engined aircraft. For propeller-powered aircraft, the equivalent term has classically been the "power loading," expressed as the weight of the aircraft divided by its horsepower (W/hp).

- Power loading has an opposite connotation from *T/W* because a high-power loading indicates a smaller engine. Power loadings typically range from 10-15 for most aircraft. An aerobatic aircraft may have a power loading of about six. A few aircraft have been built with power loadings as low as three or four. One such over-powered airplane was the Pitts Sampson, a one-of-a-kind airshow airplane.

- A propeller-powered aircraft produces thrust via the propeller, which has an efficiency ηP defined as the thrust output per horsepower provided by the engine. Using Eq(a) an equivalent *TIW* for propellered aircraft can therefore be expressed as follows:

$$\frac{T}{W} = \left(\frac{550\,\eta_p}{V}\right)\left(\frac{hp}{W}\right) \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_(a)}$$

- Note that this equation includes the term hp/ *W*, the horsepower-to weight ratio. This is simply the inverse of the classical power loading (*WI*hp). To avoid confusion when discussing requirements affecting both jet and propeller-powered aircraft, this refers to the horsepower-to weight ratio rather than the classical power loading. The reader should remember that the power loading can be determined simply by inverting the horsepower-to-weight ratio.

1.19- STATISTICAL ESTIMATION OF T/W

- Tables 1.5 and 1.6 provide typical values for *T/*Wand hp/W for different classes of aircraft. Table Y also provides reciprocal values, i.e., power loadings, for propellered aircraft. These values are all at maximum power settings at sea level and zero velocity ("static").

Aircraft type	Typical installed T/W
Jet trainer	0.4
Jet fighter (dogfighter)	0.9
Jet fighter (other)	0.6
Military cargo/bomber	0.25
Jet transport	0.25

TABLE 1.4: Thrust – To – Weight Ratio T/W

Aircraft type	Typical hp/W	Typical power loading (W/hp)
Powered sailplane	0.04	25
Homebuilt	0.08	12
General aviation—single engine	0.07	14
General aviation—twin engine	0.17	6
Agricultural	0.09	11
Twin turboprop	0.20	5
Flying boat	0.10	10

TABLE 1.5 Horse – Power – To –Weight Ratio

- Thrust-to-weight ratio is closely related to maximum speed. Later in the design process, aerodynamic calculations of drag at the design maximum speed will be used, with other criteria, to establish the required *T/W*.

- For now, Tables 1.6 and 1.7 provide curve-fit equations based upon maximum Mach number or velocity for different classes of aircraft. These can be used as a first estimate for *T/W* or hp/W. The equations were developed by the author using data from Ref. 1, and should be considered valid only within the normal range of maximum speeds for each aircraft class.

$T/W_0 = a\,M_{max}^C$	a	C
Jet trainer	0.488	0.728
Jet fighter (dogfighter)	0.648	0.594
Jet fighter (other)	0.514	0.141
Military cargo/bomber	0.244	0.341
Jet transport	0.267	0.363

TABLE: 1.6: T/W_0 vs M_{max}

$hp/W_0 = a\ V_{max}^C$	a	C
Sailplane—powered	0.043	0
Homebuilt—metal/wood	0.005	0.57
Homebuilt—composite	0.004	0.57
General aviation—single engine	0.024	0.22
General aviation—twin engine	0.034	0.32
Agricultural aircraft	0.008	0.50
Twin turboprop	0.012	0.50
Flying boat	0.029	0.23

TABLE 1.7 - hp/W_0 vs V_{max} (mph)

1.20- THRUST MATCHING

- For aircraft designed primarily for efficiency during cruise, a better initial estimate of the required T/W can be obtained by "thrust matching". This refers to the comparison of the selected engine's thrust available during cruise to the estimated aircraft drag.
- In level uncelebrated flight, the thrust must equal the drag. Likewise; the weight must equal the lift (assuming that the thrust is aligned with the flight path) Thus, T/W must equal the inverse of L/D eon (a)

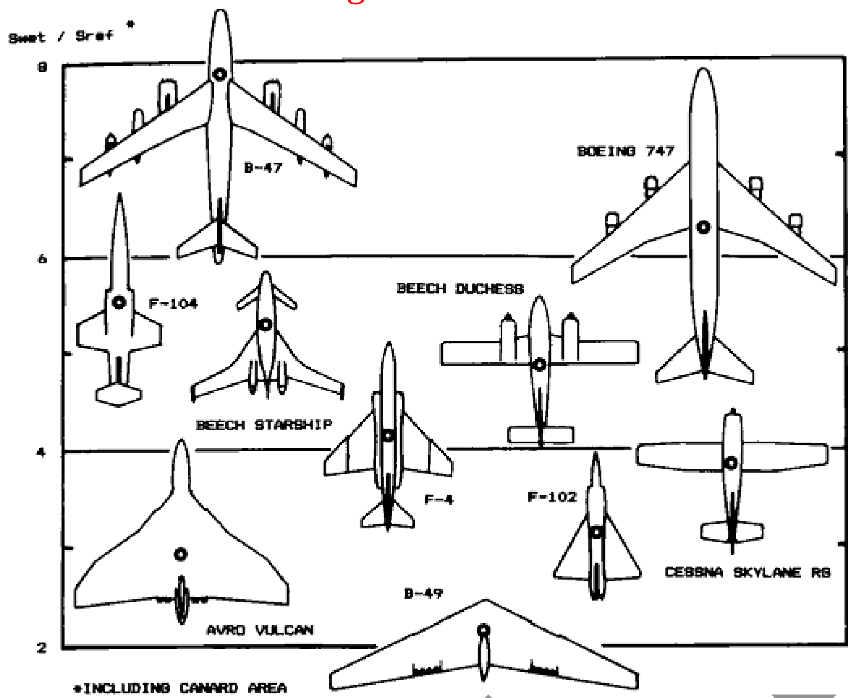
$$\left(\frac{T}{W}\right)_{cruise} = \frac{1}{(L/D)_{cruise}}$$

______ (a)

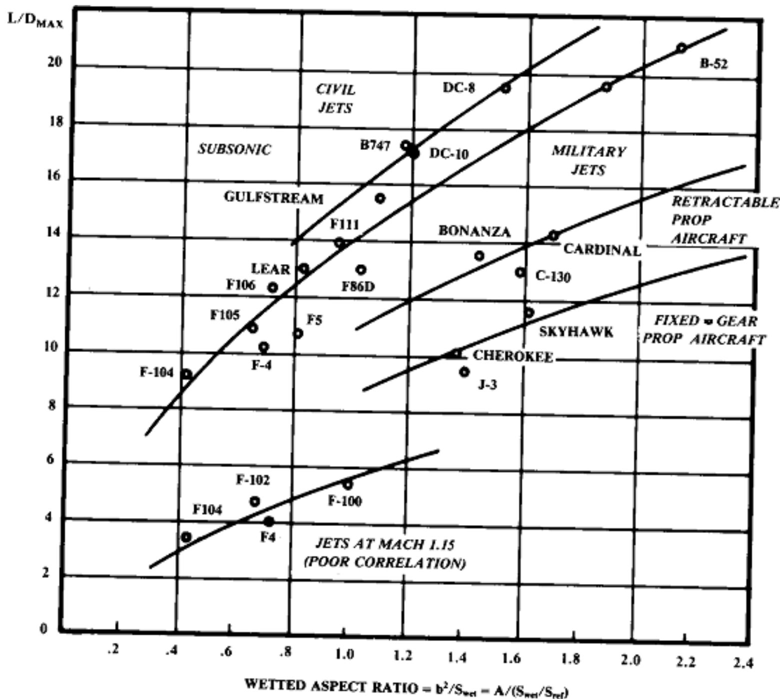
- L/D can be estimated in a variety of ways.

- Recall that this procedure for L/D estimation uses the selected aspect ratio and an estimated wetted area ratio fig a-1 .to determine the wetted aspect ratio .fig a.2 is then used to estimate the maximum L/D .for propeller aircraft, the cruise L/D is the same as the maximum L/D .for jet aircraft, the cruise L/D is 86% of the maximum L/D

Fig 1.32: Wetted Area Ratios



- Note that this method assumes that the aircraft is cruising at approximately the optimum altitude for the as – yet – unknown wing loading. The method would be invalid if the aircraft were forced by the mission requirements to cruise at some other altitude, such as sea level
- When the wing loading has been selected, the L/D at the actual cruise conditions should be calculated and used to recheck the initial estimate for T/W.



Figa-1.33.: Maximum lift to Drag Ratio Trends

- The thrust –to-weight ratio estimated using equation (a) is at cruise conditions, not take off. The aircraft will have burned off part of its fuel before beginning the cruise, and will burn off more as the cruise progresses. Also, the thrust of the selected engine will be different at the cruise conditions than at sea level , static conditions .These factors must be considered to arrive at the required take off T/W , used to size the engine .
- The highest weight during cruise occurs at the beginning of the cruise. The weight of the aircraft at the beginning of the cruise is takeoff weight less the fuel burned during takeoff and climb to cruise altitude. From table range trade the typical mission weight fractions for these mission legs are 0.979 and 0.985 or 00.956 when multiplied together
- A typical aircraft will therefore have a weight at the beginning of cruise of about 0.956 times the takeoff weight. This value is used below to adjust the cruise T/W back to take off condition . For example, a non-supercharged engine at 10,000 ft will have about 73% of its sea level.
- The take-off T/W required for cruise matching can now be approximated using equation (b) . the ratio between initial cruise and take off weight was shown to about 0.956. If a better estimate of this ratio is available it should be used .

$$\left(\frac{T}{W}\right)_{\text{takeoff}} = \left(\frac{T}{W}\right)_{\text{cruise}} \left(\frac{W_{\text{cruise}}}{W_{\text{takeoff}}}\right) \left(\frac{T_{\text{takeoff}}}{T_{\text{cruise}}}\right) \qquad \text{(b)}$$

- The thrust ratio between take off and cruise conditions should be obtained from actual engine data if possible.

- For a propeller aircraft , the required take – off hp/W can be found by combining equations 1 and 2 from below mentioned

$$\frac{T}{W} = \left(\frac{550\,\eta_p}{V}\right)\left(\frac{\text{hp}}{W}\right)$$

$$\left(\frac{T}{W}\right)_{\text{cruise}} = \frac{1}{(L/D)_{\text{cruise}}}$$

$$\left(\frac{\text{hp}}{W}\right)_{\text{takeoff}} = \left(\frac{V_{\text{cruise}}}{550\,\eta_p}\right)\left(\frac{1}{(L/D)_{\text{cruise}}}\right)\left(\frac{W_{\text{cruise}}}{W_{\text{takeoff}}}\right)\left(\frac{\text{hp}_{\text{takeoff}}}{\text{hp}_{\text{cruise}}}\right)$$

where typically $\eta_p = 0.8$.

- After an initial layout has been completed, actual aerodynamic calculations are made to compare the drag during cruise with the thrust available.

- There are many other criteria which can set the thrust – to – weight ratio such as climb rate, take off distances, and turning performance. These other criteria also involve the wing loading and are described in sub sections.

1.21- WING LOADING

- The wing loading is the weight of the aircraft divided by the area of the reference wing. As with the thrust – to – weight ratio, the term wing loading" normally refers to the takeo ff wing loading, but can also refer to combat and other flight conditions

- Wing loading affects stall speed, climb rate, takeoff and landing distances, and turn performance. The wing loading determines the design lift coefficient, and impacts drag through its effect upon wetted area and wing span.

- Wing loading has a strong effect upon sized aircraft take off gross weight.

- If the wing loading is reduced, the wing is larger. This may improve performance, but the additional drag and empty weight due to the larger wing will increase take off gross weight to perform the mission. The leverage effect of the sizing equation will require a more – than – proportional weight increase when factors such as drag and empty weight are increased.

Historical trends	Typical takeoff W/S (lb/ft^2)
Sailplane	6
Homebuilt	11
General aviation—single engine	17
General aviation—twin engine	26
Twin turboprop	40
Jet trainer	50
Jet fighter	70
Jet transport/bomber	120

- Table above provides representative wing loadings. Wing loading and thrust – to – weight ratio must be optimized together.

- These methods estimate the wing loading required for various performance conditions. To ensure that the wing provided enough lift in all circumstances, the designer should select the lowest of the estimated wing loadings. However, if an unreasonably low wing loading value is driven by only one of these performance conditions, the designer should consider another way to meet that condition.

- For example, if the wing loading required to meet a stall speed requirement is well below all other requirements. It may be better to equip the aircraft with a high lift flap system. If take off distance or rate of climb require a very low wing loading, perhaps the thrust – to – weight ratio should be increased.

1.22 STALL SPEED:

The stall speed of an aircraft is directly determined by the wing loading and the maximum lift coefficient. Stall speed is a major contributor to flying safety with a substantial number of fatal accidents each year due to "failure to maintain flying speed". Also, the approach speed which is the most important factor in landing distance and also contributes to post-touchdown accidents, is defined by the stall speed.

Civil and military design specifications establish maximum allowable stall speeds for various classes of aircraft. The approach speed is required to be a certain multiple of the stall speed. For civil applications, the approach speed must be at least 1.3 times the stall speed. For military applications, the multiple must be at least 1.2 (1.15 for carrier- based aircraft)

The below equation states the lift equals weight in level flight and that at stall, the aircraft is at maximum lift coefficient.

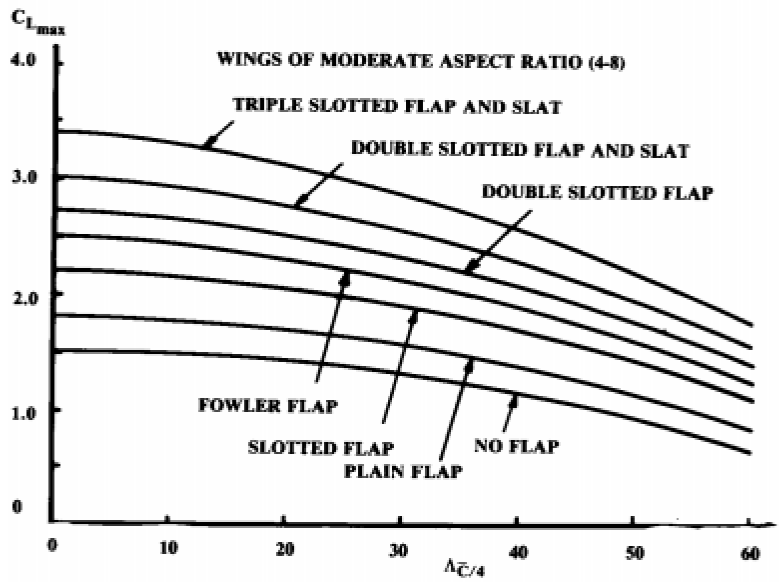
$$W = L = q_{stall} S C_{L_{max}} = {}^{1}/_{2}\ \rho V_{stall}^{2} S C_{L_{max}}$$

The required wing loading to attain a given stall speed with a certain maximum lift coefficient. The air density ρ, is typically the sea-level standard value.

$$W/S = 1/2\ \rho V_{stall}^2 C_{L_{max}}$$

The remaining unknown, the maximum lift coefficient, is very difficult to estimate. Values range from about 1.2 to 1.5 for a plain wing with no flaps to as much as 5.0 for a wing with large flaps immersed in the jet wash.

The maximum lift coefficient for an aircraft designed for short takeoff and landing (STOL) applications will typically be about 3.0. For a regular transport aircraft with flaps and slats, the maximum lift coefficient is about 2.4. Other aircraft, with flaps on the inner part of the wing, will reach a lift coefficient of about 1.6-2.0.



After Ref. 39

Fig. 5.3 Maximum lift coefficient.

Maximum lift coefficient depends upon the wing geometry, airfoil shape, flap geometry and span, leading edge slot or slat geometry, Reynolds number, surface texture and interference from other parts of the aircraft such as the fuselage, nacelles or pylons.

The maximum lift can be estimated by determining the maximum angle of attack before some part of the wing stalls. This crude approximation for wings of a fairly high aspect ratio is given by

$$C_{L_{max}} = 0.9\left\{(C_{L_{max}})_{flapped}\ \frac{S_{flapped}}{S_{ref}} + \ (C_t)_{unflapped}\frac{S_{unflapped}}{S_{ref}}\right\}$$

Where $C_{t\ unflapped}$ is the lift coefficient of the unflapped airfoil at the angle of attack at which the flapped airfoil stalls.

1.23 TAKEOFF DISTANCE

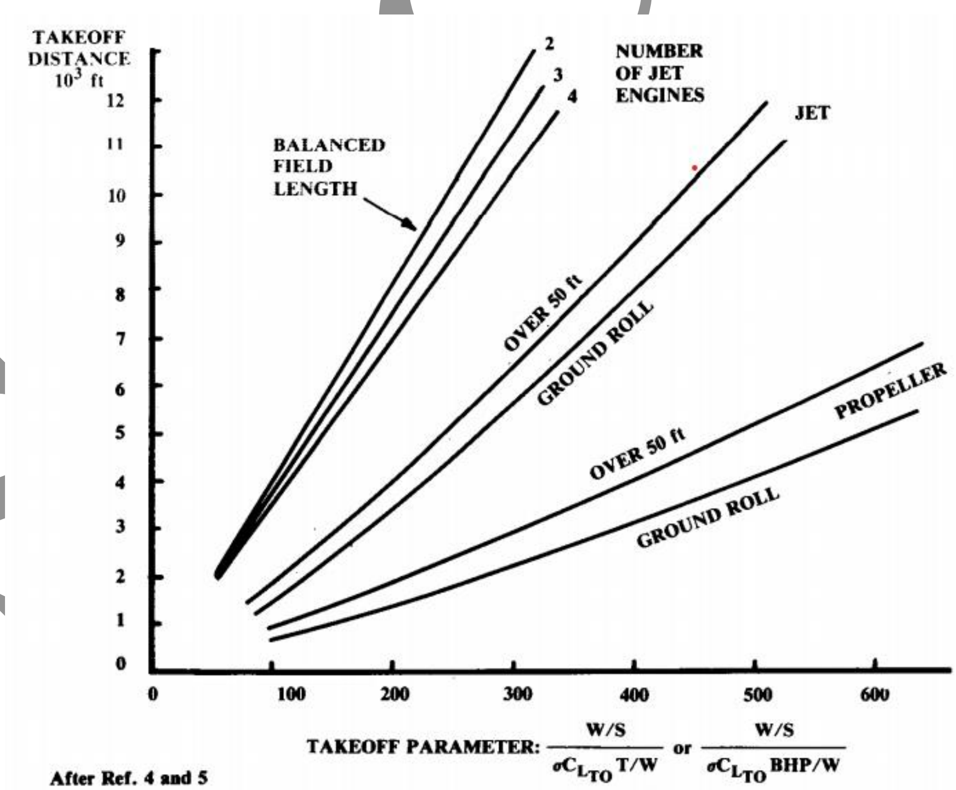
A number of different values are referred to as "takeoff distance". The "ground roll" is the actual distance traveled before the wheels leave the ground. The liftoff speed for a normal takeoff is 1.1 times the stall speed.

The "obstacle clearance distance" is the distance required from brake release until the aircraft has reached some specified altitude. The "balanced field length" is the length of the field required for safety in the event of an engine failure at the worst possible time in a multiengine aircraft.

The speed at which the distance to stop after an engine failure exactly equals the distance to continue the takeoff on the remaining engines is called the "decision speed".

Both the wing loading and the thrust-to-weight ratio contribute to the takeoff distance. The equations below assume that the thrust-to-weight ratio has been selected and can be sued to determine the required the wing loading to attain some required takeoff distance. However, the equations can be solved for T/W if the wing loading is known.

Other factors contributing to the takeoff distance are the aircraft's aerodynamic drag and rolling resistance. The aircraft's rolling resistance μ is determined by the type of runway surface and by the type, number, inflation pressure and arrangement of the tyres.



To determine the required wing loading to meet a given takeoff distance requirement, the takeoff parameter is obtained for the above graph. Then the following expressions give the maximum allowable wing loading for the given takeoff distance:

$$\text{Prop:} \quad (W/S) = (\text{TOP})\sigma C_{L_{\text{TO}}}(\text{hp}/W)$$

$$\text{Jet:} \quad (W/S) = (\text{TOP})\sigma C_{L_{\text{TO}}}(T/W)$$

Where σ – density ratio

C_{LTO} – Lift Coefficient at Take Off

TOP – Take Off Parameter

1.24 CATAPULT TAKEOFF

Most Naval aircraft must be capable of operation from an aircraft carrier. For takeoff from a aircraft carrier, a catapult accelerates the aircraft to flying speed in a very short distance. Catapults are steam operated and can produce a maximum force on the aircraft depending on the steam pressure used. Therefore, a light aircraft can be accelerated to a higher speed by the catapult than a heavy one.

For a catapult takeoff, the airspeed as the aircraft leaves the catapult must exceed the stall speed by 10%. Airspeed is the sum of the catapult end speed (V_{end}) and the wind-over-deck of the carrier (V_{wod})

Once the end speed is known, the maximum wing loading is defined by

$$\left(\frac{W}{S}\right)_{\text{landing}} = \frac{1}{2}\rho(V_{\text{end}} + V_{\text{wod}})^2 \frac{(C_{L\,\max})_{\text{takeoff}}}{1.21}$$

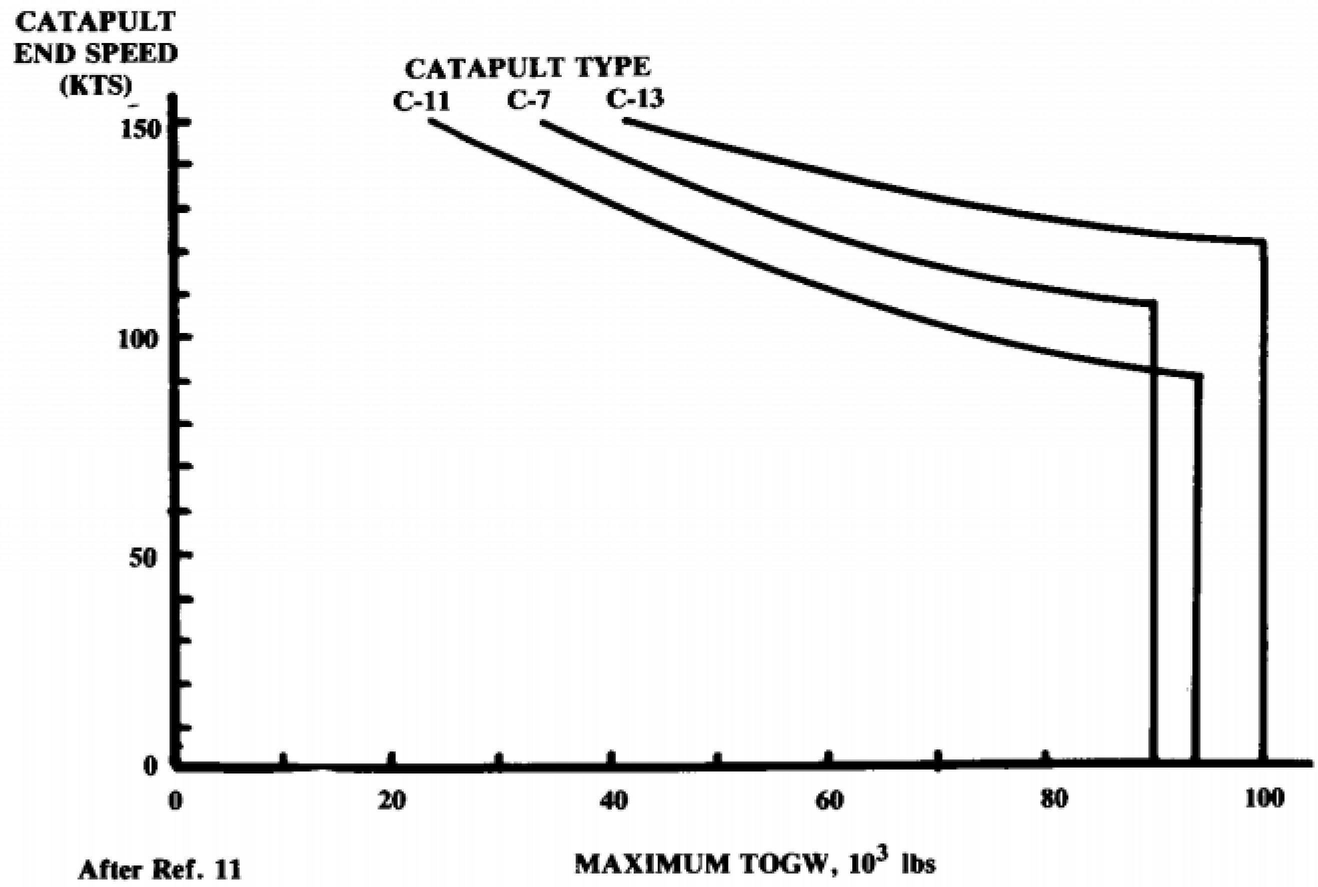


Fig. 5.5 Catapult end speeds.

1.25 LANDING DISTANCE

There are a number of different values referred to as the "landing distance". "Landing ground roll" is the actual distance the aircraft travels from the time the wheels first touch to the time the aircraft comes to a complete stop.

Landing distance is largely determined by wing loading. Wing loading affects the approach speed, which must be a certain multiple of stall speed (1.3 for civil aircraft, 1.2 for military aircraft). Approach speed determines the touchdown speed, which in turn defines the kinetic energy which must de dissipated to bring the aircraft to a halt. The kinetic energy and hence the stopping distance varies as the square of the touchdown speed.

The below equation provides a better approximation of the landing distance, which can be used to estimate the maximum landing wing loading. The first term represents the ground roll to absorb the kinetic energy at touchdown speed. The constant term, S_a represents the obstacle-clearance distance.

$$S_{\text{landing}} = 80\left(\frac{W}{S}\right)\left(\frac{1}{\sigma C_{L_{\max}}}\right) + S_a$$

Where S_a = 1000 (airliner type, 3-deg glideslope)
= 600 (general aviation-type power off approach)
= 450 (STOL, 7-deg glidescope)

1.26 WING LOADING FOR CRUISE

Two aerodynamic coefficients C_{Do} and "e" are brought to use. C_{Do} is the zero lift drag coefficient, and equals approximately 0.015 for a jet aircraft, 0.02 for a clean propeller aircraft and 0.03 for dirty, fixed gear propeller aircraft. The Oswald efficiency factor e is a measure of drag due to lift efficiency and equals approximately 0.6 for fighter and 0.8 for other aircraft.

To maximize range, a propeller aircraft should fly such that,

$$qSC_{D_0} = qS\,\frac{C_L^2}{\pi Ae}$$

During cruise, the lift equals the weight, so the lift coefficient equals the wing loading divided by the dynamic pressure. This substitution into the above equation allows solution for the required wing loading to maximize L/D for a given flight condition. This result is the wing loading for maximum range for a propeller aircraft as below.

$$\textbf{Maximum Prop Range:}\quad W/S = q\sqrt{\pi AeC_{D_0}}$$

As the aircraft cruises, its weight reduces due to the fuel burned, so the wing loading also reduces during cruise. Optimizing the cruise efficiency while the wing loading is steadily declining requires reducing the dynamic pressure by the same percent. This can be done by reducing the velocity which is undesirable or by climbing to obtain a lower air density. This range optimizing technique is known as "cruise-climb".

A jet aircraft flying a cruise-climb will obtain maximize range by flying at a wing loading such that the parasite drag is three times the induced drag. This yields the following formula for wing loading selection for range optimization of jet aircraft.

$$\textbf{Maximum Jet Range:}\quad W/S = q\sqrt{\pi AeC_{D_0}/3}$$

Frequently an aircraft will not be allowed to use the cruise-climb technique to maximize range. Air Traffic Controllers prefer that aircraft maintain a single assigned altitude until given permission to climb or descend to another altitude.

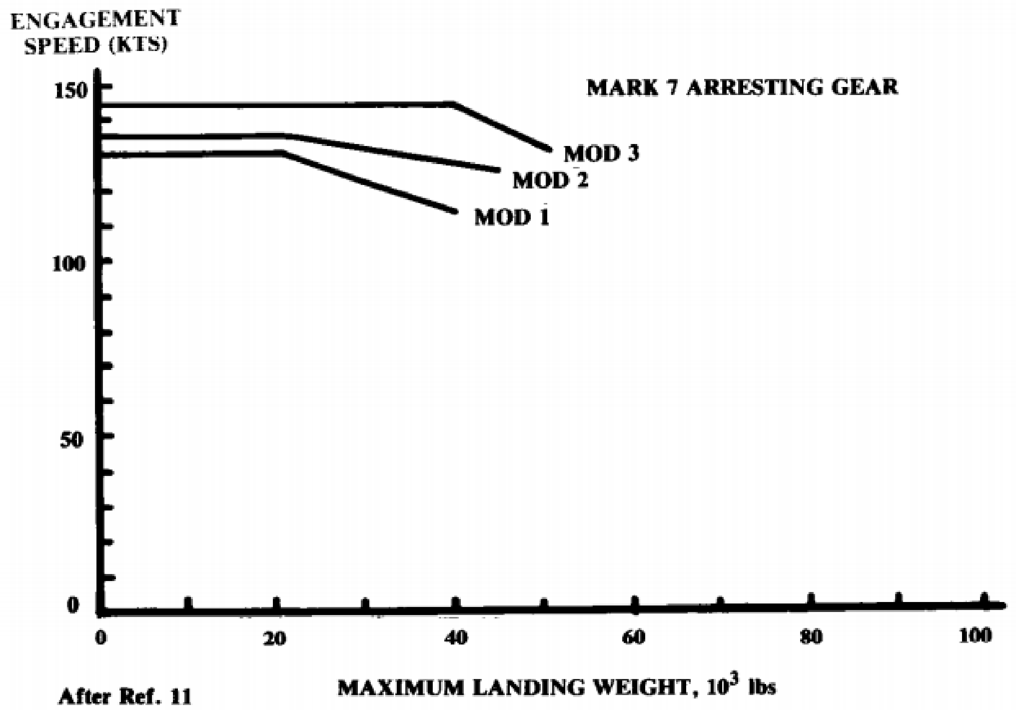


Fig. 5.6 Arresting gear weight limits.

1.27 WING LOADING FOR LOITER ENDURANCE

Most aircraft will have some loiter requirement during the mission, typically 20 min of loiter before landing. For an aircraft which must be optimized for loiter, the wing loading should be selected to provide a high L/D. For jet aircraft, the best loiter occurs at maximum L/D, the below equations are used which provides the wing loading for minimum power required.

$$\text{Maximum Jet Loiter: } W/S = q\sqrt{\pi A e C_{D_0}}$$

$$\text{Maximum Prop Loiter: } W/S = q\sqrt{3\pi A e C_{D_0}}$$

These equations assume that the loiter velocity and altitude are known. If the loiter altitude is not specified, it should be selected for best specific fuel consumption at the loiter power setting.

1.28 INSTANTANEOUS TURN:

An aircraft designed for air-to-air dogfighting must be capable of high turn rate. This parameter, dψ/dt or ψ, will determine the outcome of a dogfight if the aircraft and pilots are evenly matched otherwise.

When air-to air missiles are in use, the first aircraft to turn towards the other aircraft enough to launch a missile will probably win. In a guns-only dogfight, the aircraft with the higher turn rate will be able to maneuver behind the other. A turn rate superiority of 2deg/s is considered significant.

There are two important turn rates. The "sustained" turn rate for some flight condition is the turn rate at which the thrust of the aircraft is just sufficient velocity and altitude in the turn. If the thrust acts approximately opposite to the flight direction, then the thrust must equal the drag for a sustained turn.

If the aircraft turns at a quicker rate, the drag becomes greater than the available thrust, so the aircraft begins to slow down or lose altitude. The "instantaneous" turn rate is the highest turn rate possible, ignoring the fact that the aircraft will slow down or lose altitude.

Turn rate is equal to the radial acceleration divide by the velocity. For a level turn, this results in the below equation which provides turn rate in radians per second.

$$\dot{\psi} = \frac{g\sqrt{n^2 - 1}}{V}$$

where

$$n = \frac{qC_L}{W/S}$$

The required wing loading can be solved for as follows

$$\frac{W}{S} = \frac{qC_{L_{\max}}}{n}$$

The resulting wing loading is the maximum which will allow the required instantaneous turn.

1.29 SUSTAINED TURN:

The sustained turn rate is also important for success in combat. It two aircraft pas each other in opposite directions, it will take them about 10 second to complete 1580-deg turns back towards the other. The aircraft will probably not be able to maintain speed while turning at the maximum instantaneous rate, if one of the aircraft slows down below corner speed during this time it will be at a turn rate disadvantage to the other, which could prove fatal.

Sustained turn rate is usually expressed in terms of the maximum load factor at some flight condition that the aircraft can sustain without slowing or losing altitude. If speed is to be maintained, the thrust must equal the drag and the lift must equal the weight times the load factor, thus

$$n = (T/W)\,(L/D)$$

Sustained-turn load factor is maximized by maximizing the T/W and L/D. the highest L/D occurs when the induced drag equals the parasite drag. During a turn, the lift equals the weight times n, so the lift coefficient equals the wing loading times n divided by the dynamic pressure. Thus

$$W/S = \frac{q}{n}\sqrt{\pi A e C_{D0}}$$

$$\frac{T}{W} = \frac{qC_{D0}}{W/S} + \frac{W}{S}\left(\frac{n^2}{q\pi Ae}\right)$$

$$\frac{W}{S} = \frac{(T/W) \pm \sqrt{(T/W)^2 - (4n^2 C_{D0}/\pi Ae)}}{2n^2/q\pi Ae}$$

If the term within the square root becomes negative, there is no solution. This implies that, at a given load factor, the following must be satisfied regardless of the wing loading

$$\frac{T}{W} \geq 2n\sqrt{\frac{C_{D_0}}{\pi Ae}}$$

1.30 CLIMB AND GLIDE

The numerous climb requirements specify rate of climb for various combinations of factors such as engine-out, landing gear position and flap settings. While the details may vary, the method for selecting a wing loading to satisfy such requirements is the same.

Rate of climb is the vertical velocity, typically expressed in feet per minute. Climb gradient "G" is the ratio between vertical and horizontal distance travelled. At normal climb angles the climb gradient equals the excess thrust divided by the weight ie.,

$$G = (T - D)/W$$

or

$$\frac{D}{W} = \frac{T}{W} - G$$

D/W can also be expressed as in the below equation, where in the final expression the lift coefficient is replaced by W/qS

$$\frac{D}{W} = \frac{qSC_{D_0} + qS(C_L^2/\pi Ae)}{W} = \frac{qC_{D0}}{W/S} + \frac{W}{S}\frac{1}{q\pi Ae}$$

Equating the above two equations and solving for wing loading yields

$$\frac{W}{S} = \frac{[(T/W) - G] \pm \sqrt{[(T/W) - G]^2 - (4C_{D0}/\pi Ae)}}{2/q\pi Ae}$$

The term within the square root symbol cannot be less than zero, so the following must be true regardless of the wing loading.

$$\frac{T}{W} \geq G + 2\sqrt{\frac{C_{D0}}{\pi Ae}}$$

1.31. MAXIMUM CEILING

The above can be used to calculate the wing loading to attain some maximum ceiling, given the T/W at those conditions. The climb gradient G can be set to zero to represent level flight at the desired altitude. For a high-altitude aircraft such as an atmospheric research or reconnaissance plane, the low dynamic pressure available may determine the minimum possible wing loading.

The following equation can be sued to determine the wing loading for minimum power

$$W/S = q\sqrt{\pi AeC_{D_0}}$$

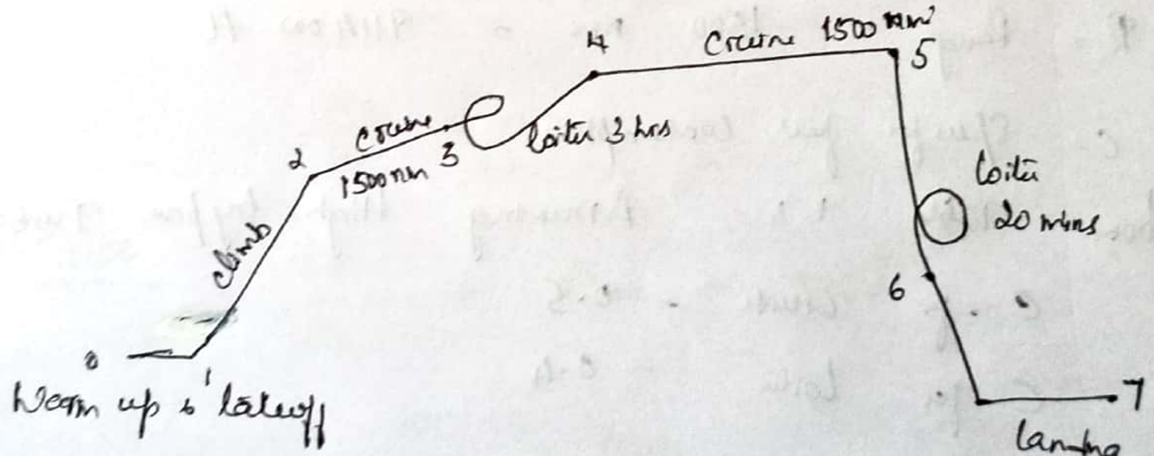
The value obtained from the above equation should be compared with the wing loading required to fly at a given lift coefficient ie.,

$$W/S = qC_L$$

Flight Vehicle Design - 17AE82

Module - I . Problems

① Fig illustrates the mission requirement for a hypothetical Anti-Submarine Warfare (ASW) aircraft. The key requirements is the ability to loiter for three hours at a distance of 1500 n.mi from the takeoff point. While loitering on-station this type of aircraft uses sophisticated electronic equipment to detect and track submarines. For the sizing example, this equipment is assumed to weigh 10,000 lbs. Also a four man crew is required, totalling 800 lbs. The aircraft cruises at 0.6 Mach number.



Soln:-

W.K.T

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - W_f/W_0 - W_e/W_0}$$

$W_{crew} = 800$ lbs

$W_{payload} = 10{,}000$ lbs] Given

To find W_f/W_0

W.K.T $\frac{W_f}{W_0} = 1.06\left(1 - W_x/W_0\right)$

$W_x/W_0 \cdot W_7/W_0 = W_1/W_0 \cdot \frac{W_2}{W_1} \cdot \frac{W_3}{W_2} \cdot \frac{W_4}{W_3} \cdot \frac{W_5}{W_4} \cdot \frac{W_6}{W_5} \cdot \frac{W_7}{W_6}$

1) Warm up + Take off

$\frac{W_1}{W_0}$ - for Warmup + takeoff

$= 0.97$

from Table 1.2 - Historical mission segment weight fractions

Warmup + takeoff - 0.97

2) Climb: $W_2/W_1 = 0.985$

from Table 1.2, for climb $W_i/W_{i-1} = 0.985$

3) Cruise $W_3/W_2 = e^{\left[-RC/V \times L/D\right]}$

R - Range = 1500 nmi = 9114000 ft

C - Specific fuel consumption

from Table 1.3, Assuming High-bypass Turbofan engine

C - for cruise - 0.5

C - for loiter - 0.4

V - Velocity = 0.6×Mach number - given

= 0.6 × velocity of sound

= 0.6 × 994.8

= 569.9 ft/s

$\therefore \frac{W_3}{W_2} = e^{-\left[\frac{9114000 \times 0.5}{569.9 \times 0.866 \times 16}\right]}$

$e^{(-0.095)}$

L/D_{max} is assumed as 16.

For a jet engine,

$L/D_{cruise} = 0.866\, L/D_{max} = 0.866 \times 16$

$L/D_{loiter} = L/D_{max} = \underline{\underline{13.856}}$

$$\frac{W_3}{W_2} = e^{-\cancel{0.095}}$$

$$= \underline{\underline{0.91}}$$

4) <u>Loiter:</u> $E = 3$ hours $= 10{,}800$ s.

$C = 0.4$ /hr $= 0.000111$ /s.

$L/D_{loiter} = L/D_{max} = 16$

$$\frac{W_4}{W_3} = e^{\left[-EC/L_D\right]}$$

$$= e^{\left[-\frac{10{,}800 \times 0.000111}{16}\right]}$$

$$= e^{-0.075}$$

$$\frac{W_4}{W_3} = \underline{\underline{0.9277}}$$

5) <u>Cruise</u> $\frac{W_5}{W_4}$ - Same as No 3

$$\therefore \frac{W_5}{W_4} = 0.91$$

6) <u>Loiter:</u> $E = 20$ mins $= 1200$ s.

$C = 0.000111$ /s

$L/D_{loiter} = L/D_{max} = 16.$

$$\frac{W_6}{W_5} = e^{\left[-EC/L_D\right]} = e^{\left[-\frac{1200 \times 0.000111}{16}\right]}$$

$$\frac{W_6}{W_5} = e^{-0.008325}$$

$$= \underline{\underline{0.9917}}$$

7) <u>landing</u> $\frac{W_7}{W_6} = \underline{\underline{0.995}}$

from Table 1.2.

$$\frac{W_i}{W_{i-1}} \text{ for landing} = 0.995$$

$$\frac{W_7}{W_0} = \frac{W_1}{W_0} \times \frac{W_2}{W_1} \times \frac{W_3}{W_2} \times \frac{W_4}{W_3} \times \frac{W_5}{W_4} \times \frac{W_6}{W_5} \cdot \frac{W_7}{W_6}$$

$$= 0.97 \times 0.985 \times 0.91 \times 0.9277 \times 0.91 \times 0.9917 \times 0.995$$

$$= 0.7242$$

$$\therefore \frac{W_f}{W_0} = 1.06 \left(1 - W_x/W_0\right)$$

$$= 1.06 \left(1 - 0.7242\right)$$

$$\frac{W_f}{W_0} = \underline{\underline{0.2923}}$$

$$\frac{W_e}{W_0} = A W_0^{C} K_{VS}$$

from Table 1.1. Empty weight fraction V/s W_0

for military Cargo / Bomber

$$A = 0.93, \quad C = -0.07$$

& $K_{VS} = 1.00$ if fixed sweep

$$\therefore \frac{W_e}{W_0} = 0.93 \, W_0^{-0.07}$$

$$\therefore W_0 = \frac{W_{crew} + W_{payload}}{1 - W_f/W_0 - W_e/W_0}$$

$$= \frac{800 + 10000}{1 - 0.2923 - 0.93 W_0^{-0.07}}$$

W_0 given	W_e/W_0	W_0 calculated
50,000	0.43606	66,264
60,000	0.4305	64,864
59,200	0.4309	64,958
59,800	0.4310	65,052

Iterate the value of W_e/W_0 & W_0 calculated for different values of W_0, so that W_0 given & W_0 calculated is approximately same.