10. CLASS I WEIGHT AND BALANCE ANALYSIS

The purpose of this chapter is to familiarize the reader with a rapid method to determine whether or not the center of gravity of the proposed airplane design is in 'the right place' for different loading scenarios.

The method is referred to as a Class I weight and balance method and is to be used in conjunction with Step 10 of p.d. sequence I as outlined in Chapter 2.

Section 10.1 presents the method as a 9-step procedure. Example applications are given in Section 10.2.

10.1 CLASS I WEIGHT AND BALANCE METHOD

Step 10.1: Using Class I component weight prediction methods, determine the initial component weight breakdown of the airplane.

Part V (Ref.4), Chapter 2 shows how a Class I component weight breakdown can be prepared. Table 10.1a shows a list of weight components which are typically found in a Class I weight breakdown. Three numerical examples of Class I component weight breakdowns are presented in Section 10.2.

Table 10.1a Typical Class I Component Weight Breakdown

1. Fuselage group
2. Wing group
3. Empennage group
4. Engine group
5. Landing gear group
6. Fixed equipm't group

Empty weight: $W_E = \sum_{i=1}^{i=6} W_i$

7. Trapped fuel and oil
8. Crew

Operating weight empty: $W_{OE} = \sum_{i=1}^{i=8} W_i$

9. Fuel
10. Passengers
11. Baggage
12. Cargo
13. Military load

Take-off weight: $W_{TO} = \sum_{i=1}^{i=13} W_i$

Step 10.2: Prepare a preliminary arrangement drawing of the airplane using the drawings developed in Chapters 5-9.

Figure 10.1 shows a conceptual preliminary arrangement drawing as used in a typical weight and balance analysis. Figure 10.1 is drawn as a threeview because of the asymmetry of that configuration. For many symmetrical airplanes a sideview is sufficient.

Step 10.3: Locate the centers of gravity of all Class I weight components in Figure 10.1.

Note: some airplanes have severe asymmetries in their weight distribution. In that case it will also be necessary to locate the y locations of the component c.g.'s.

At this point, Figure 10.1 is also referred to as a 'c.g. threeview'.

Step 10.4: Enter the appropriate x,y and z coordinates of each component c.g. in a table such as Table 10.1b.

Table 10.2 provides some guidance for locating component c.g.'s of major weight groups. Further guidance to finding the location of component c.g.'s can be found in Chapter 2 of Part V (Ref.4).

CAUTION: Make absolutely certain that the zero reference point as shown in Figures 10.1 is always selected so that all coordinates are positive. To assure that this will be so even for future growth versions of the airplane, 'pick' the zero reference point well to the left and well below the nose of the airplane.

The author has seen both engineers in industry and aeronautical engineering design students make the most awful 'sign' errors as a result of not selecting the zero reference point as suggested here.

The following nomenclature is widely used in the aircraft industry:

x-coordinates as defined in Figure 10.1 are referred to as fuselage stations (F.S.).

y-coordinates as defined in Figure 10.1 are referred to as wing buttock lines (B.L. or W.B.L.).

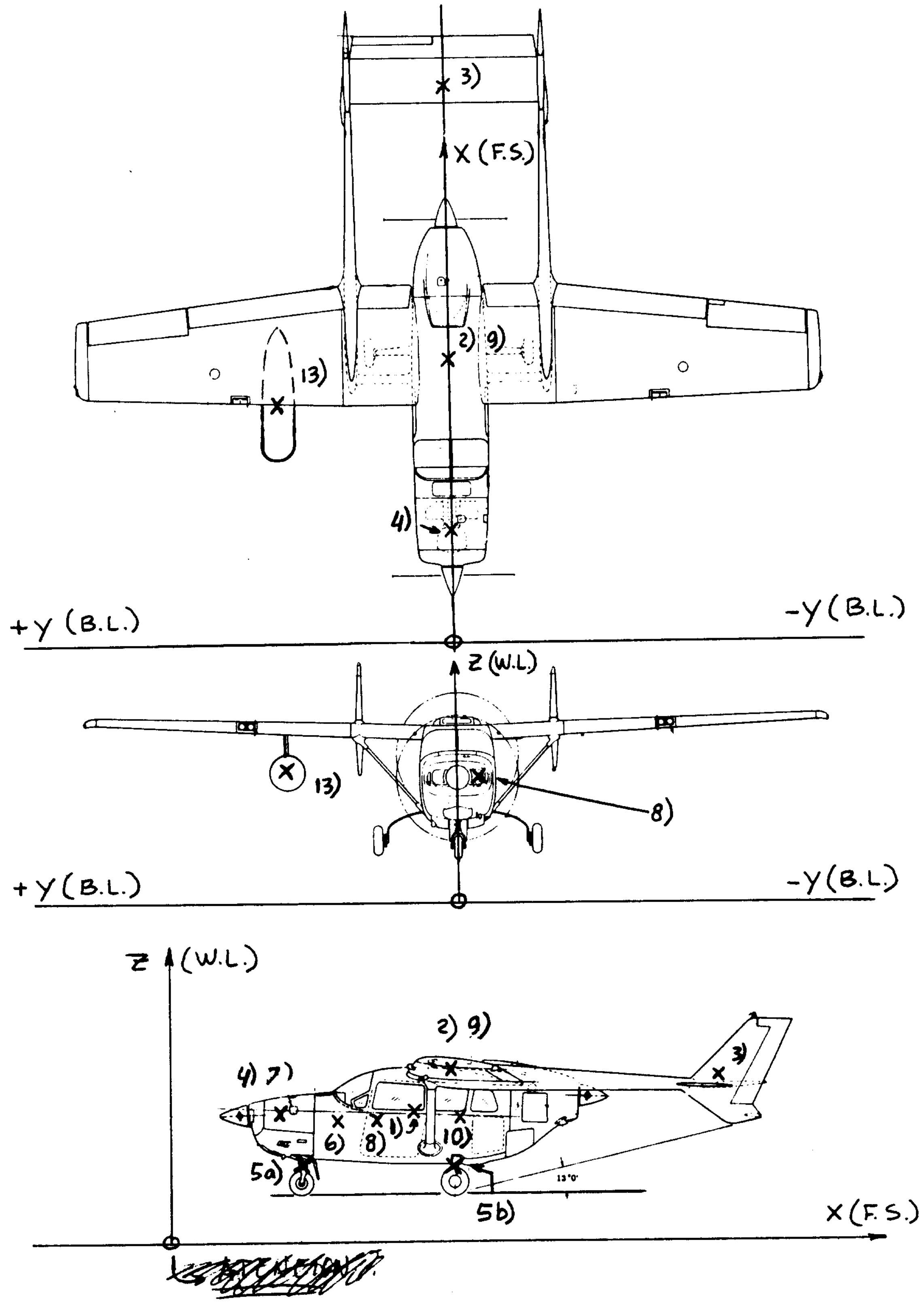


Figure 10.1 Preliminary Configuration Arrangement

Table 10.1b Class I Weight and Balance Calculation

No.	Type of Component	W_i	x_i	$W_i x_i$	y_i	$W_i y_i$	z_i	$W_i z_i$
		lbs	in.	inlbs	in.	inlbs	in.	inlbs
1.	Fuselage group	W_1	x_1	$W_1 x_1$	y_1	$W_1 y_1$	z_1	$W_1 z_1$
2.	Wing group							
3.	Empennage group							
4.	Engine group							
5.	Landing gear group							
6.	Fixed equipm't group							

Empty weight: $W_E = \text{Sum}_{i=1}^{i=6} W_i$ $\qquad$ $x_{cg_{W_E}} = (\text{Sum}_{i=1}^{i=6} W_i x_i)/W_E$

No.	Type of Component
7.	Trapped fuel and oil
8.	Crew

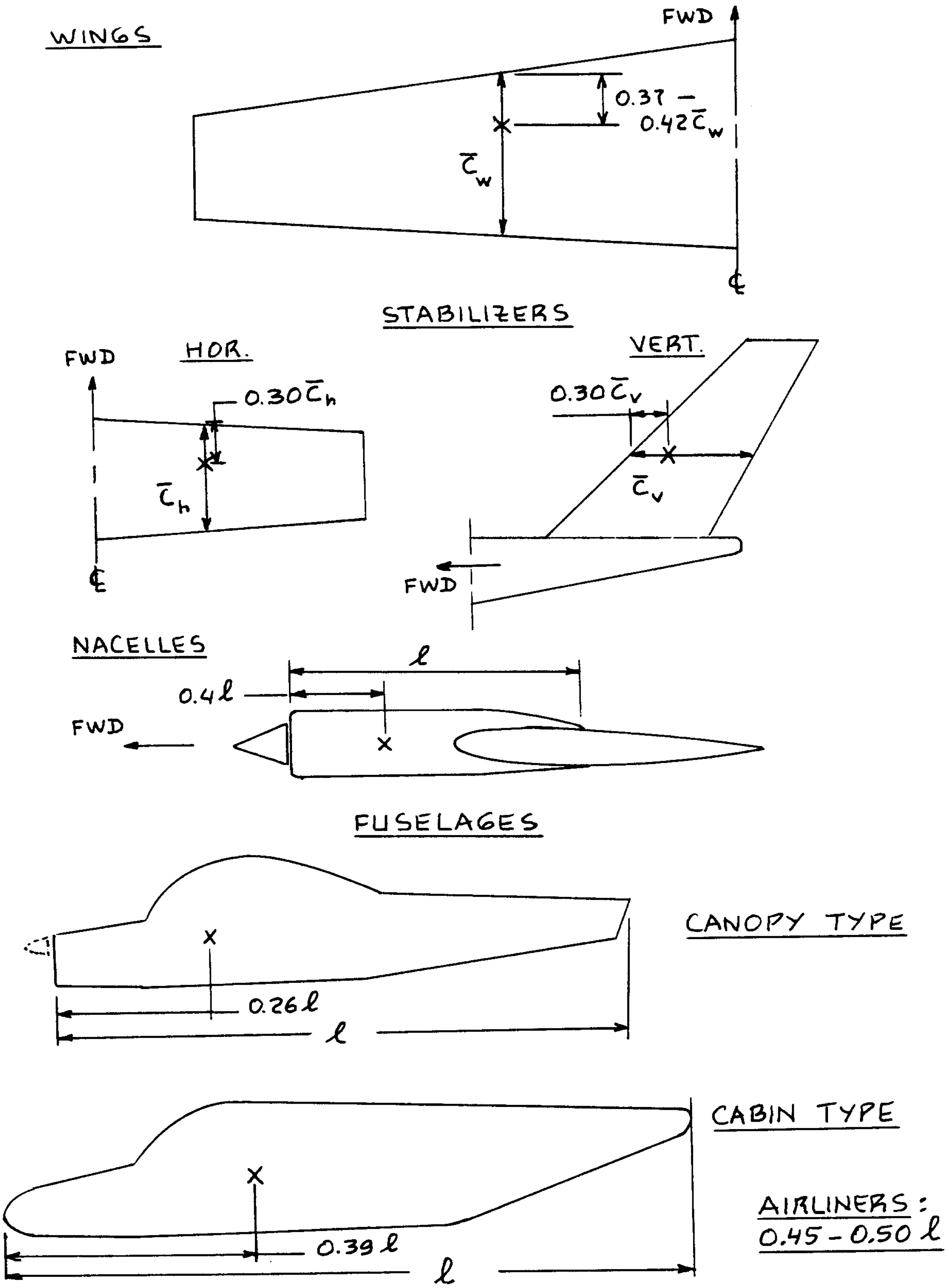
Operating weight empty: $W_{OE} = \text{Sum}_{i=1}^{i=8} W_i$ $\qquad$ $x_{cg_{W_{OE}}} = (\text{Sum}_{i=1}^{i=8} W_i x_i)/W_{OE}$

No.	Type of Component
9.	Fuel
10.	Passengers
11.	Baggage
12.	Cargo
13.	Military load

Take-off weight: $W_{TO} = \text{Sum}_{i=1}^{i=13} W_i$ $\qquad$ $x_{cg_{W_{TO}}} = (\text{Sum}_{i=1}^{i=13} W_i x_i)/W_{TO}$

Note: Locations for y_{cg} and for z_{cg} are found from similar equations.

Table 10.2 Location of C.G.'s of Major Components



z-coordinates as defined in Figure 10.1 are referred to as water lines (W.L.). This term is a carry-over from the ship building industry.

<u>Step 10.5:</u> Calculate the x_{cg}, y_{cg} and z_{cg} of the airplane with the help of Table 10.1b.

These c.g. locations must be calculated for <u>all</u> feasible loading scenarios. These loading scenarios depend to a large extent on the mission of the airplane. Typical loading combinations are:

1. Empty weight
2. Empty weight + crew
3. Empty weight + crew + fuel
4. Empty weight + crew + fuel + payload = Take-off weight

The reader will realize that these four loading combinations give rise to the following six loading scenarios:

1 2 3 4	1 3 2 4	1 4 2 3
1 2 4 3	1 3 4 2	1 4 3 2

In reality there can be many more depending on:

1. the type of payload and the way it can be stowed: (for example passengers piling into a Boeing 747)

2. the way the fuel tankage is arranged and how the fuel can be sequenced in and out.

Examples of typical loading scenarios are given in Section 10.2.

<u>Step 10.6:</u> Construct a weight-c.g. excursion diagram for the proposed airplane.

Figure 10.2 shows an example of a typical c.g. excursion diagram. It is important to identify in this diagram the loading sequences as well as the critical weights such as W_E and W_{TO}. Note also in Figure 10.2 that the c.g. locations are plotted as follows:

1. in terms of fuselage station (F.S.)

and:

2. in terms of a fraction of the wing mean geometric chord, $\bar{c}_w$.

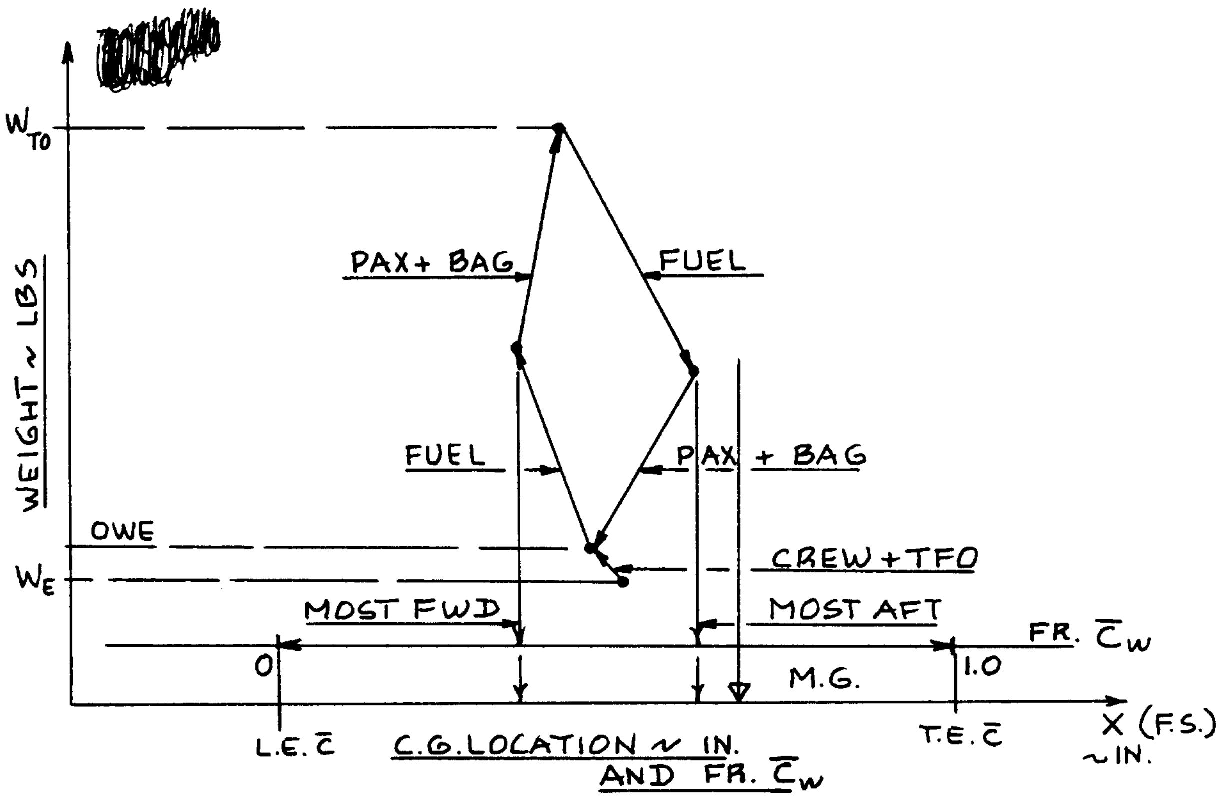


Figure 10.2 Weight-C.G. Excursion Diagram

Table 10.3 Examples of Center of Gravity Ranges

Type	C.G. Range (in.)	C.G. Range fr. $\bar{c}_w$	Type	C.G. Range (in.)	C.G. Range fr. $\bar{c}_w$
Homebuilts	5	0.10	Military Trainers	8	0.10
Single Engine Prop. Driven	7-18	0.06-0.27	Fighters	15	0.20
Twin Engine Prop. Driven	9-15	0.12-0.22	Mil.Patr. Bomb and Transp.	26-90	0.30
Ag. Airpl.	5	0.10	Fl.Boats, Amph. and Float	7-28	0.25
Business Jets	8-17	0.10-0.21			
Regional TBP	12-20	0.14-0.27	Amph. and		
Jet Transp.	26-91	0.12-0.32	Supersonic Cruise	20-100	0.30

Note also in Figure 10.2 that the main landing gear location is identified. This is important to determine if there is a longitudinal 'tip-over' problem.

For some airplanes it may be important to also draw c.g. excursion diagrams which reflect the vertical and lateral c.g. situations. These c.g. situations may have an impact on the landing gear disposition because of lateral tip-over potential.

<u>Step 10.7:</u> Determine the most forward and the most aft c.g. location of the airplane. Compare the resulting c.g. range with the c.g. ranges of other airplanes in the same category.

Figure 10.2 is used to determine where the most forward and most aft c.g. locations are. The reader will now understand why it is vital to have 'smoked' out the most adverse loading scenarios which are consistent with the mission of the airplane.

Table 10.3 presents data for comparing the resulting c.g. range with the c.g. ranges of other airplanes.

<u>Step 10.8:</u> Draw conclusions about the feasibility of the proposed airplane arrangement and if necessary make changes.

In judging the feasibility of the proposed airplane arrangement the following principles must be kept in mind:

<u>Principle 1:</u>

Where possible, the ideal c.g. arrangement is one for which the OWE-c.g., the fuel-c.g. and the payload-c.g. are in the same vertical location.

The reader will find that in most airplane designs it is not possible to reach this ideal situation. One should try to come as close as possible.

<u>Principle 2:</u>

Try to position the landing gear so that no major structural cutouts are needed to retract the gear. Also: make sure that there is a sufficient amount of volume available to retract the gear into.

Principle 3:

Keep in mind that the airplane also has to satisfy certain basic stability and control requirements. Step 12 in p.d. sequence I (Chapter 2) deals with this problem. In this regard there are two types of airplanes:

1. Airplanes which must have inherent static longitudinal and static directional stability. The so-called X-plot method of Step 12 is used in conjunction with the Class I weight and balance analysis to assure inherent static stability. Keep in mind that without minimum static stability levels the proposed airplane design is invalid.

2. Airplanes which can have inherent static longitudinal and/or static directional instability. These airplanes must now have a flight control system which through the correct feedback loops signal control surface actuators to in turn move flight control surfaces in such a way that 'de-facto' stability is insured. This implies a relationship between the 'design' level of inherent instability, control power, feedback gains and actuator rate requirements. A Class I method to account for this during p.d. sequence I is discussed in Chapter 11.

Priciple 4:

If an airplane design turns out to have major balance problems it is often possible to 'fix' these problems by moving the wing. If the gear needs to be attached to the wing, the entire wing/gear combination must be moved.

Step 10.9: Document the decisions made under Steps 10.1 - 10.8 in a brief descriptive report including clear, dimensioned drawings.

10.2 EXAMPLE APPLICATIONS

Three examples will now be discussed:

10.2.1 Twin Engine Propeller Driven Airplane: Selene
10.2.2 Jet Transport: Ourania
10.2.3 Fighter: Eris

10.2.1 Twin Engine Propeller Driven Airplane

Step 10.1: Table 10.4 shows the component weight breakdown for the Selene. This breakdown is the result of applying a Class I component weight estimation method to the airplane. This method is discussed in detail in Chapter 2 of Part V (Ref.4).

Step 10.2: Figure 10.3 shows the preliminary arrangement drawing for the Selene. This drawing is the result of combining Figures 4.2, 5.3, 6.3, 8.2 and 9.3. For the Selene only the sideview is important in establishing its weight and balance characteristics.

Step 10.3: Figure 10.3 also shows the component centers of gravity.

Step 10.4: Table 10.4 also lists the x, y and z coordinates of all Selene weight components.

Step 10.5: Table 10.4 also lists the centers of gravity for several important loading configurations.

Step 10.6: Figure 10.4 shows the weight-c.g. excursion diagram for the Selene.

Step 10.7: From Figure 10.4 it follows that the c.g. limits are:

most forward c.g. occurs at W = 7,000 lbs,

F.S.= 280 in. and $0.62\bar{c}_w$

most aft c.g. occurs at W = 5,500 lbs, F.S.= 295 in.

and $0.78\bar{c}_w$

The c.g. range of the Selene is 15 inches or $0.16\bar{c}_w$.

Note that this compares favorably with the data of Table 10.3.

Table 10.4 Component Weight and Coordinate Data: Selene

Component	Weight	x	Wx	y	Wy	z	Wz
	lbs	in.	in.lbs	in.	in.lbs	in.	in.lbs
Wing	738	269	198,522	0	0	118	87,084
Empennage H.T.	120	559	67,080	0	0	189	22,680
V.T.	59	504	29,736	0	0	146	8,614
Fuselage	621	220	136,620	0	0	76	47,196
Nacelles	249	315	78,435	0	0	126	31,374
Landing Gear N.G.	76	110	8,360	0	0	47	3,572
M.G.	304	315	95,760	0	0	55	16,720
Engines + inst.	1,508	331	499,148	0	0	126	190,008
Propellers	200	362	72,400	0	0	129	25,800
Fixed Equipment	1,025	220	225,500	0	0	76	77,900
Empty weight, W_E	4,900	288	1,411,561	0	0	104	510,948
TFO	44	315	13,860	0	0	118	5,192
Fuel	1,706	276	470,856	0	0	118	201,308
2 Pax.	350	184	64,400	0	0	76	26,600
2 Pax.	350	282	98,700	0	0	76	26,600
2 Pax.	350	337	117,950	0	0	76	26,600
Baggage	200	220	44,000	14	2,800	76	15,200
Take-off wht, W_{TO}	7,900	281	2,221,327	0	2,800	103	812,448

Note: other loading conditions shown in Figure 10.4.

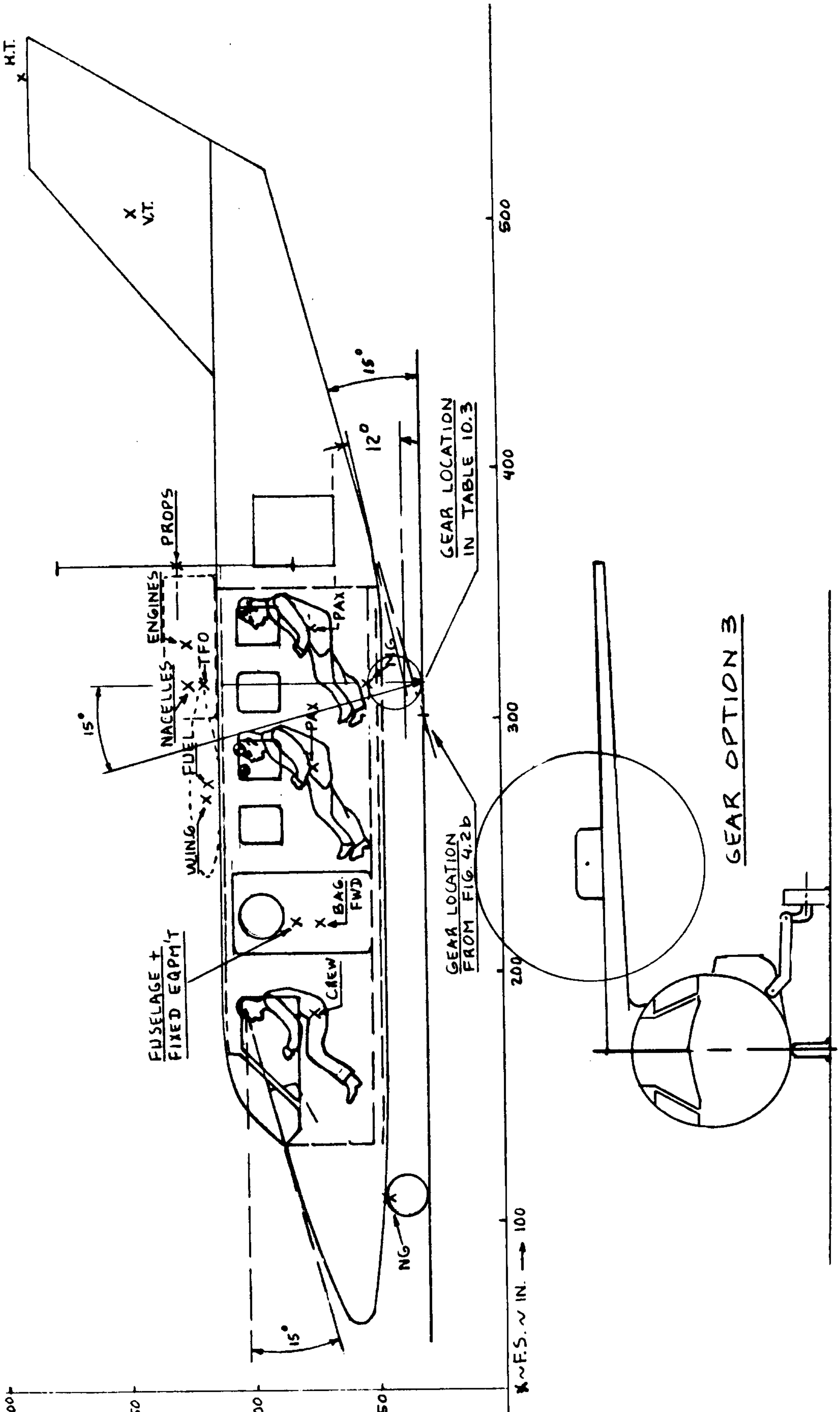


Figure 10.3 Selene: General Arrangement

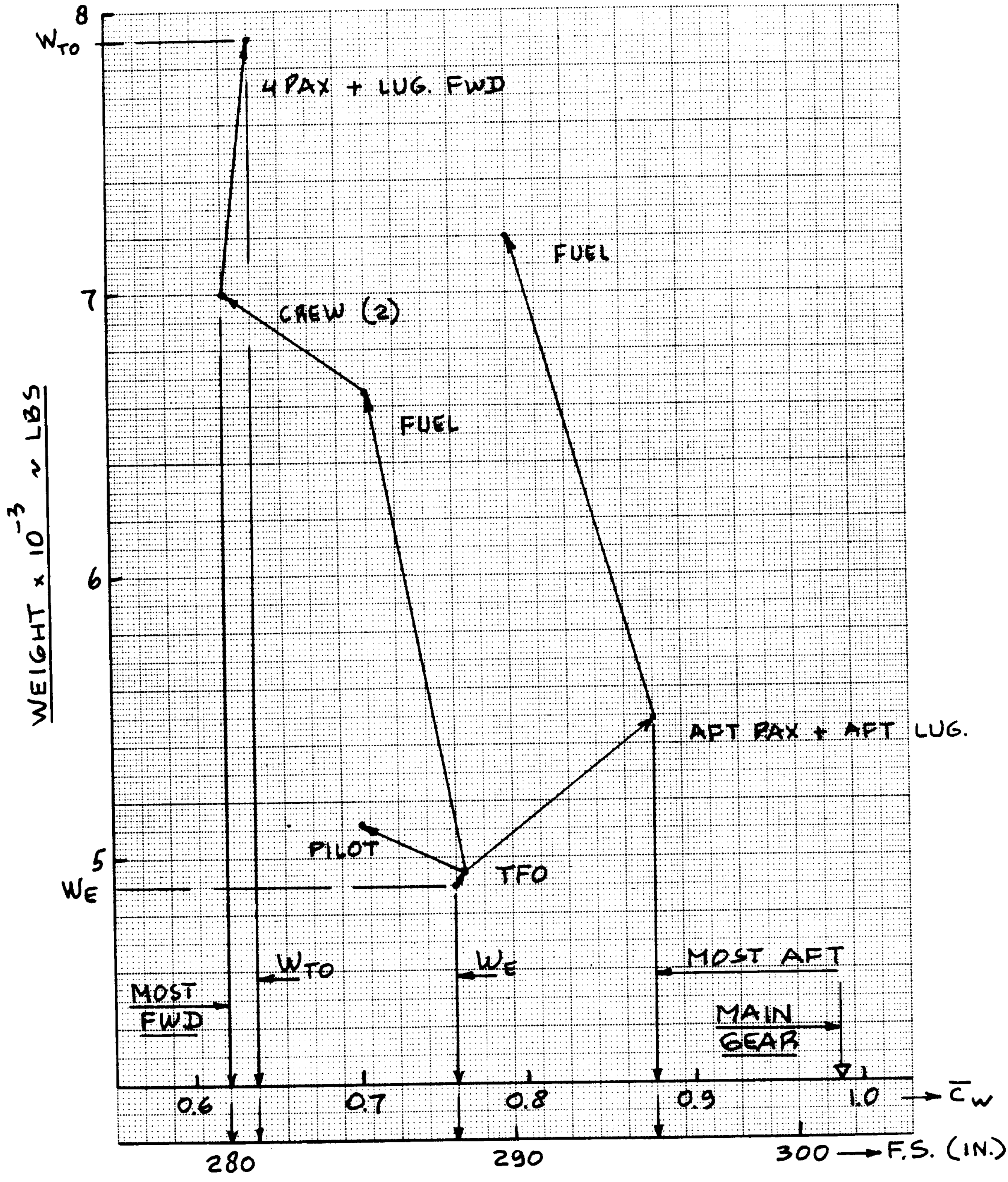


Figure 10.4 Selene: Weight-C.G. Excursion Diagram

Step 10.8: The most aft c.g. is well forward of the main landing gear contact point. The overall landing gear disposition problem relative to the c.g. range is discussed in Chapter 9, Sub-section 9.2.1.

The suitability of the aft c.g. location from a static longitudinal and static directional stability viewpoint is discussed in Chapter 11, Sub-section 11.2.1.

Step 10.9: To save space this step has been omitted.

10.2.2 Jet Transport

Step 10.1: Table 10.5 shows the component weight breakdown for the Ourania. This breakdown is the result of applying a Class I component weight estimation method to the airplane. This method is discused in detail in Chapter 2 of Part V (Ref.4).

Step 10.2: Figure 10.5 shows the preliminary arrangement for the Ourania. This drawing is the result of combining Figures 4.7, 5.5, 6.4, 8.3 and 9.5. For the Ourania only the sideview and the topview are needed to establish its weight and balance characteristics.

Step 10.3: Figure 10.5 also shows the component centers of gravity.

Step 10.4: Table 10.5 also lists the x, y and z coordinates of all Ourania weight components.

Step 10.5: Table 10.5 also lists the centers of gravity for several important loading configurations.

Step 10.6: Figure 10.6 shows the weight-c.g. excursion diagram for the Ourania.

Step 10.7: From Figure 10.6 it follows that the c.g. limits are:

most forward c.g. occurs at W = 100,000 lbs,

F.S. = 861 in. and $-0.04\bar{c}_w$.

most aft c.g. occurs at W = 100,000 lbs,

F.S. = 884 in. and $0.12\bar{c}_w$.

The c.g. range of the Ourania is seen to be 23 in.

This is equivalent to $0.16\bar{c}_w$.

Table 10.5 Component Weight and Coordinate Data: Ourania

Component	Weight	x	Wx	y	Wy	z	Wz
	lbs	in.	in.lbs	in.	in.lbs	in.	in.lbs
Wing	13,664	913	12,475,232	0	0	213	2,910,432
Empennage	3,253	1,535	4,993,355	0	0	343	1,115,779
Fuselage	14,184	866	12,283,344	0	0	248	3,517,632
Nacelles	2,082	728	1,515,696	0	0	150	312,300
Landing Gear N.G.	573	307	175,911	0	0	122	69,906
M.G.	4,632	894	4,141,008	0	0	146	676,272
Powerplant inst.	9,891	705	6,973,155	0	0	157	1,552,887
Fixed Equipment	20,171	846	17,064,666	0	0	248	5,002,408
Empty weight, W_E	68,450	871	59,622,367	0	0	221	15,157,616
TFO	925	882	815,850	0	0	173	160,025
Fuel	25,850	882	22,799,700	0	0	205	5,299,250
Crew flight deck	410	260	106,600	0	0	248	101,680
cabin att.	205	1,339	274,495	0	0	248	50,840
cabin att.	410	354	145,140	0	0	248	101,680
Pax + luggage	30,750	846	26,014,500	0	0	248	7,626,000
Take-off wht, W_{TO}	127,000	864	109,778,652	0	0	224	28,497,091

Note: other loading conditions shown in Figure 10.6.

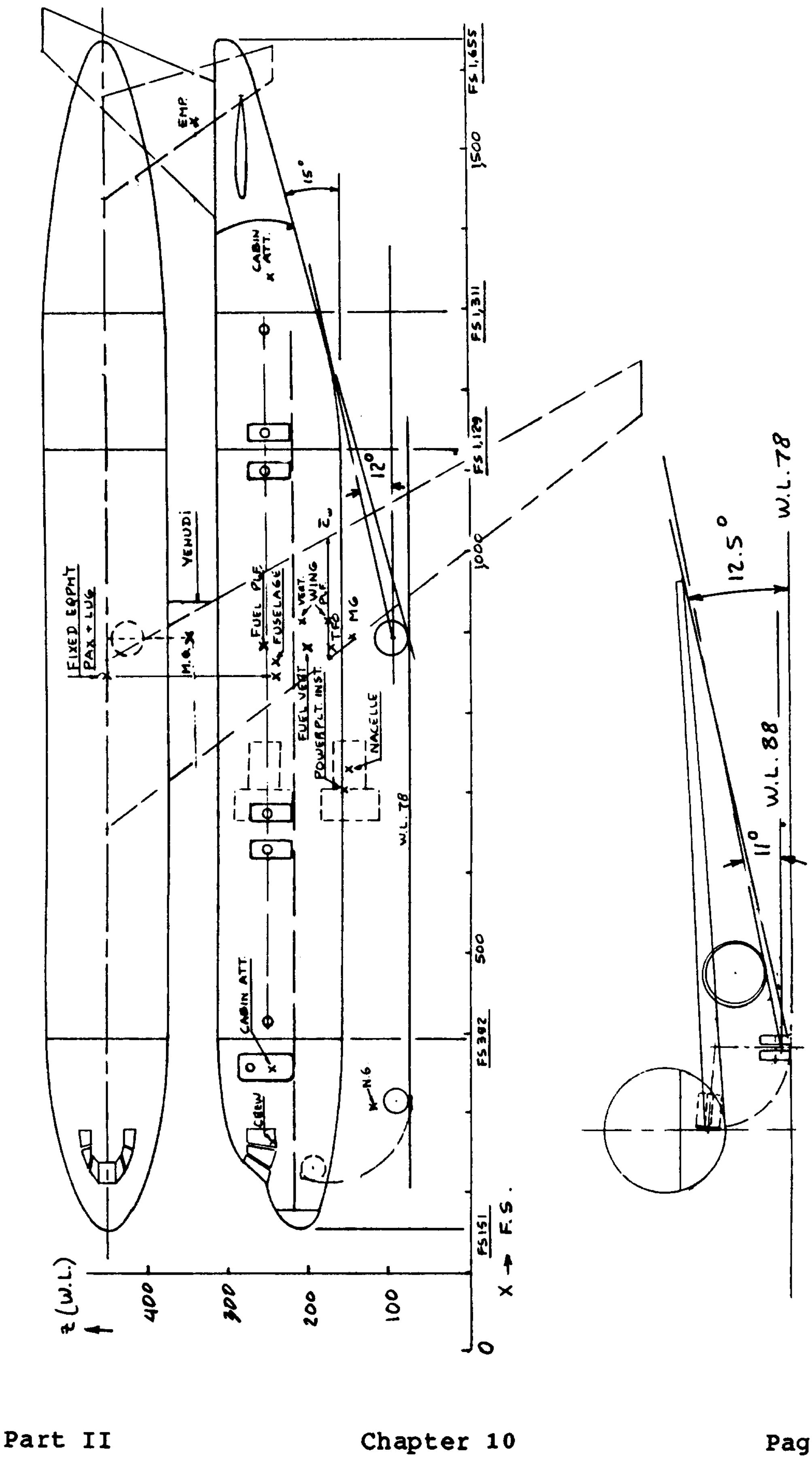


Figure 10.5 Ourania: General Arrangement

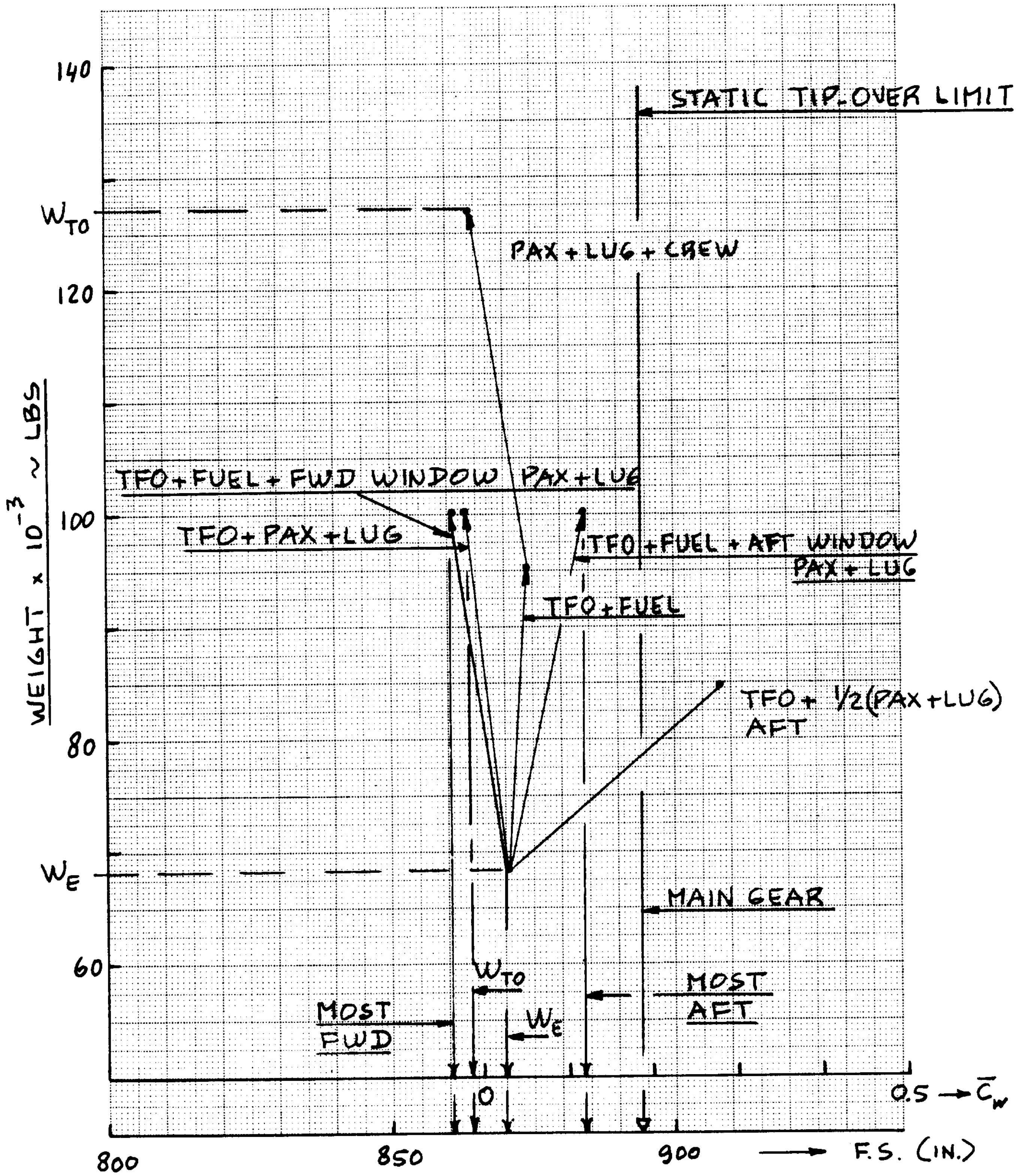


Figure 10.6 Ourania: Weight-C.G. Excursion Diagram

Note that this compares favorably with the data of Table 10.3.

Step 10.8: The most aft c.g. of the Ourania is well forward of the main gear contact point. The overall gear disposition relative to the c.g. range is discussed in Chapter 9, Sub-section 9.2.2.

The suitability of the aft c.g. location from a viewpoint of static longitudinal and static directional stability is discussed in Chapter 11, Sub-section 11.2.2.

Step 10.9: To save space this step has been omitted.

10.2.3 Fighter

Step 10.1: Table 10.6 shows the component weight breakdown for the Eris. This breakdown is the result of applying a Class I component weight estimation method to the airplane. This method is discussed in detail in Chapter 2 of Part V (Ref.4).

Step 10.2: Figure 10.7 shows the preliminary arrangement drawing for the Eris. This drawing is the result of combining Figures 4.9, 6.5, 8.4 and 9.7. Because of the asymmetries involved in the gun and nose gear placement, a front view and a top view are included in Figure 10.7.

Step 10.3: Figure 10.7 also shows the component centers of gravity.

Step 10.4: Table 10.6 also lists the x, y and z coordinates of all Eris weight components.

Step 10.5: Table 10.6 also lists the centers of gravity for several important loading configurations.

Step 10.6: Figure 10.8 shows the weight-c.g. excursion diagram for the Eris.

Step 10.7: From Figure 10.8, the c.g. limits are:

most forward c.g. occurs at W = 46,400 lbs,

F.S.= 324 in. and $0.43\bar{c}_w$.

most aft c.g. occurs at W = 33,500 lbs,

F.S.= 334 in. and $0.50\bar{c}_w$.

Table 10.6 Component Weight and Coordinate Data: Eris

Component	Weight	x	Wx	y	Wy	z	Wz
	lbs	in.	in.lbs	in.	in.lbs	in.	in.lbs
Wing	6,762	331	2,238,222	0	0	118	797,916
Empennage	1,597	614	980,558	0	0	173	276,281
Fuselage + booms	7,347	323	2,373,081	0	0	94	690,618
Engine section	160	417	66,720	0	0	91	14,560
Landing Gear N.G.	554	137	75,898	+16	8,864	44	24,376
M.G.	2,214	350	774,900	0	0	58	128,412
Engines	6,000	417	2,502,000	0	0	91	546,000
Engine inst.	2,834	370	1,048,580	0	0	102	289,068
GAU-8A Gun	2,014	180	362,520	-20	-40,280	60	120,840
Fixed Eq.(- gun)	4,018	189	759,402	0	0	85	341,530
Empty weight, W_E	33,500	334	11,181,881	-1	-31,416	96	3,229,601
TFO	300	370	111,000	0	0	85	25,500
Fuel	18,500	331	6,123,500	0	0	118	2,183,000
Pilot	200	209	41,800	0	0	91	18,200
Ammunition	1,785	283	505,155	0	0	73	130,305
Bombs (fuselage)	4,248	277	1,176,696	0	0	44	186,912
Bombs (wings)	6,372	315	2,007,180	0	0	100	637,200
Take-off wht, W_{TO}	64,905	326	21,147,212	0	-31,416	99	6,410,718

Note: other loading conditions shown in Figure 10.8.

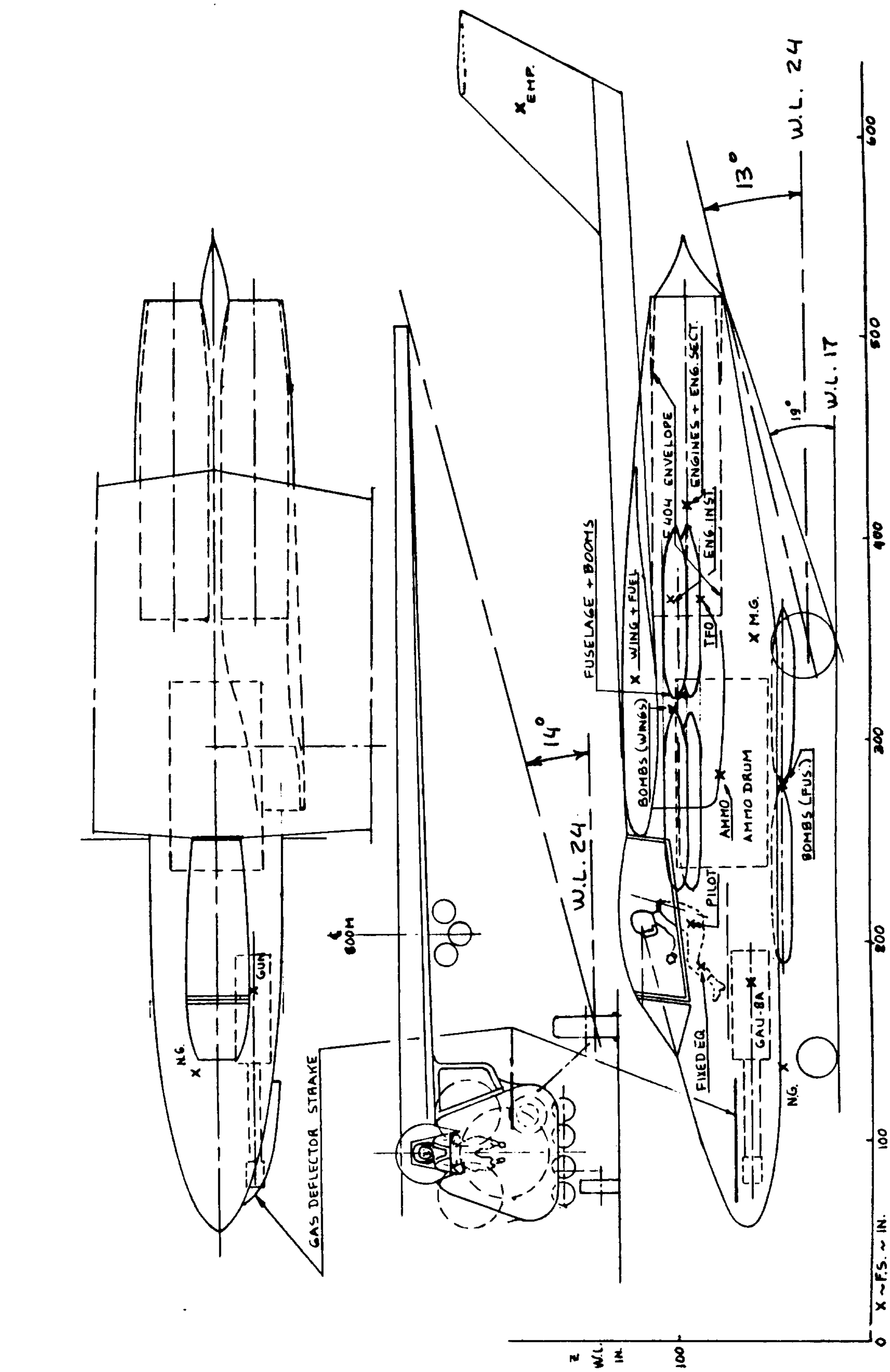


Figure 10.7 Eris: General Arrangement

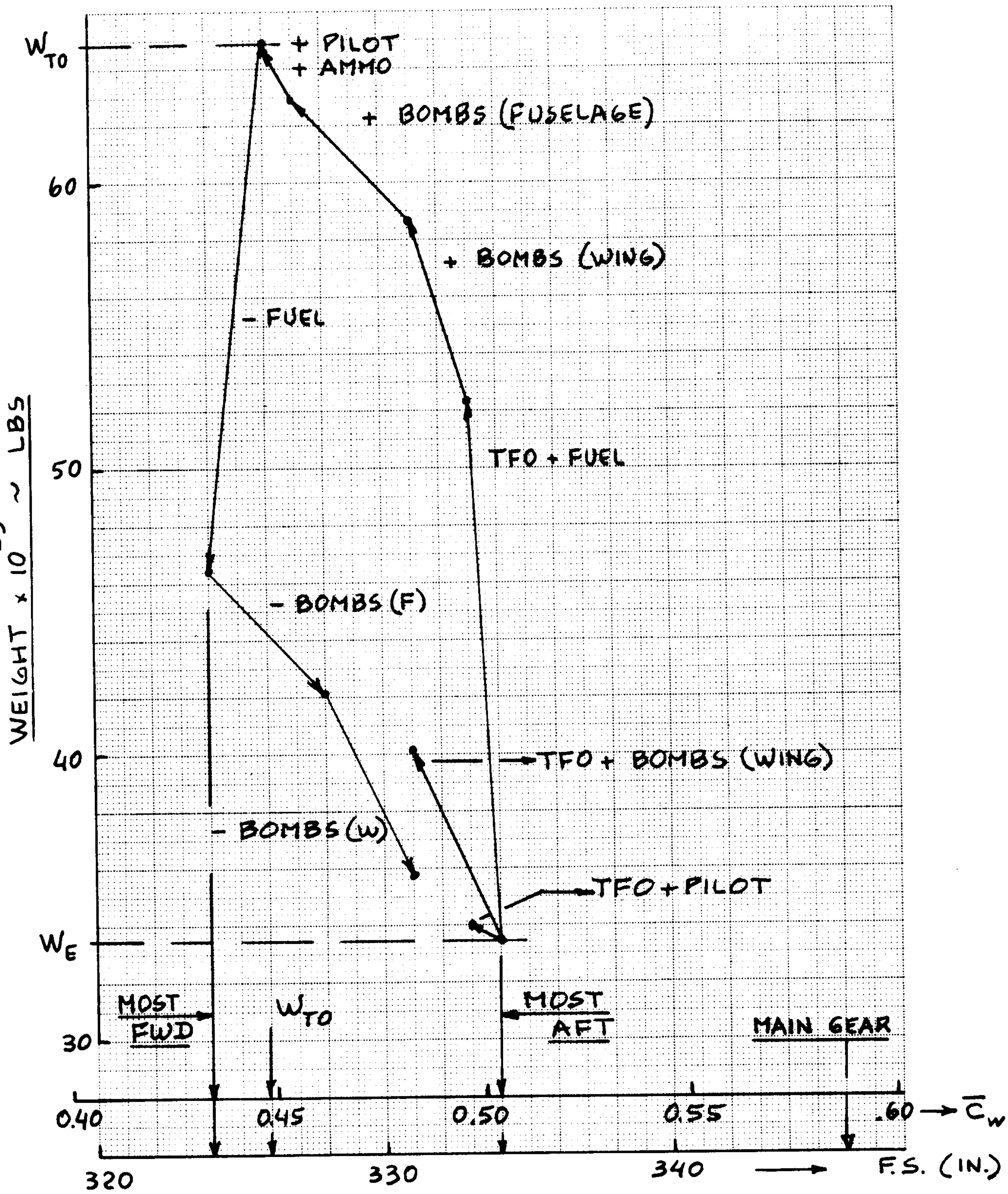


Figure 10.8 Eris: Weight C.G. Excursion Diagram

The c.g. range of the Eris is 10 inches or $0.07\bar{c}_w$.

Note that this compares favorably with the data of Table 10.3.

Step 10.8: The most aft c.g. is well forward of the main landing gear. The overall disposition of the landing gear relative to the c.g. range is discussed in Chapter 9, Sub-section 9.2.3.

The suitability of the aft c.g. location in terms of static longitudinal and static directional stability is discussed in Chapter 11, Sub-section 11.2.3.

Step 10.9: To save space this step has been omitted.

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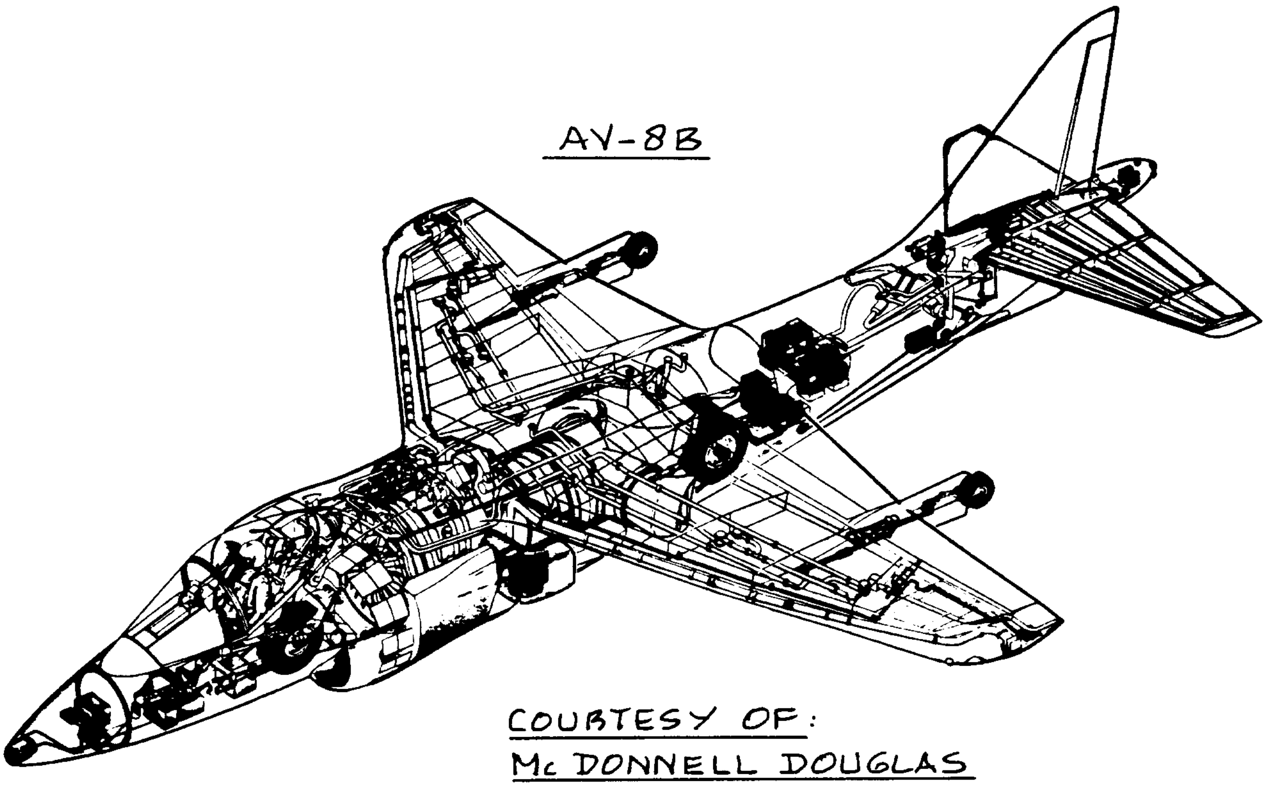

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