MARSAIRPLANE

A Crew Cabin Study by:
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Estimating Volume and Weight for a Pressurized Crew Cabin

CABIN SIZING

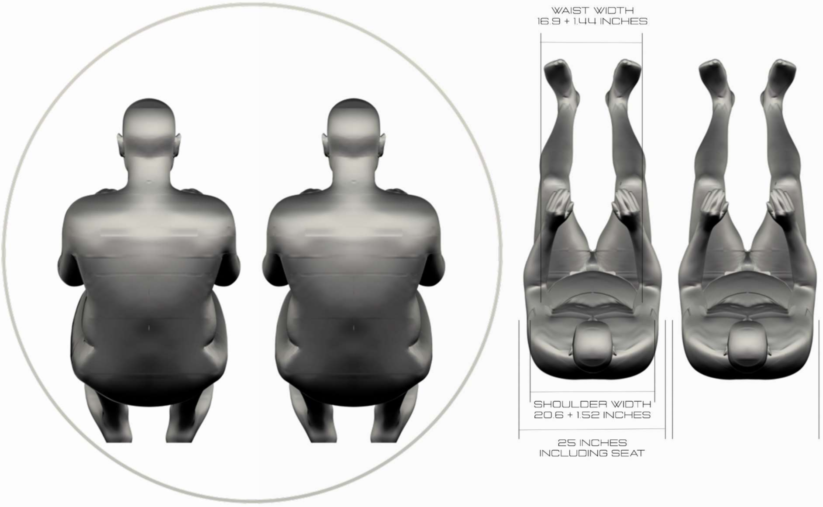
SIZED FOR 95TH PERCENTILE MALE (GLOBAL) WITH MILITARY CLOTHING

OUTER DIAMETER
4.84 FT (1475 MM)

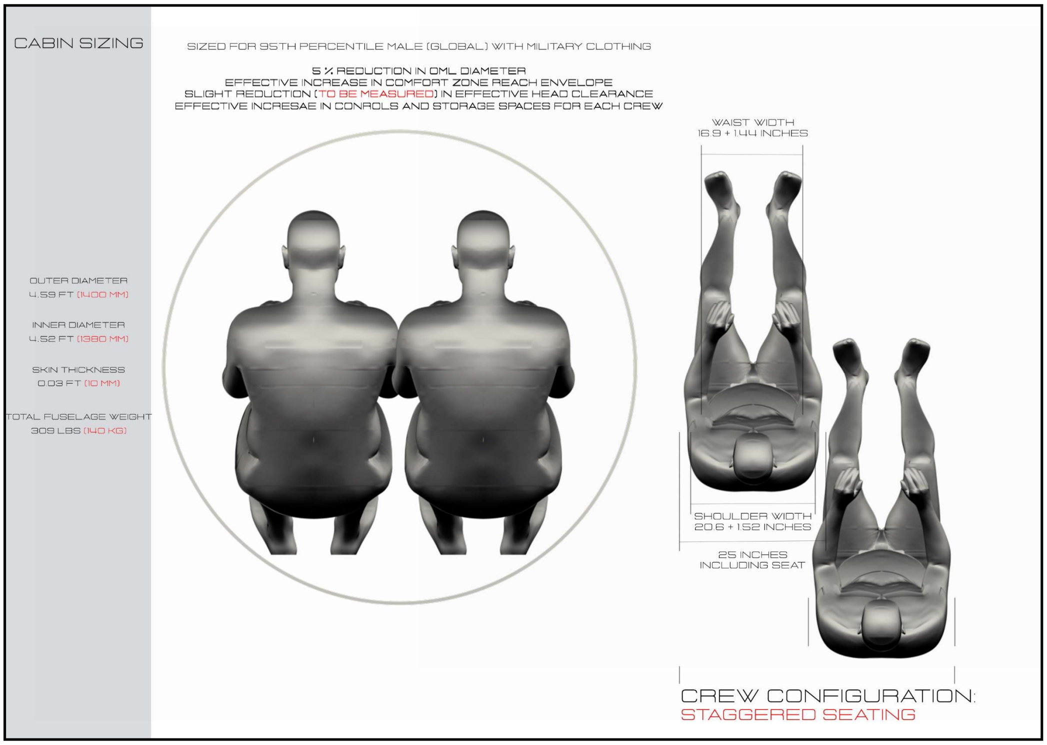
INNER DIAMETER
4.77 FT (1455 MM)

SKIN THICKNESS
0.03 FT (10 MM)

TOTAL FUSELAGE WEIGHT
336 LBS (152 KG)



CREW CONFIGURATION:
ABREAST SEATING



CABIN SIZING

SIZED FOR 95TH PERCENTILE MALE (GLOBAL) WITH MILITARY CLOTHING

5 % REDUCTION IN OML DIAMETER
EFFECTIVE INCREASE IN COMFORT ZONE REACH ENVELOPE
SLIGHT REDUCTION (TO BE MEASURED) IN EFFECTIVE HEAD CLEARANCE
EFFECTIVE INCRESAE IN CONROLS AND STORAGE SPACES FOR EACH CREW

OUTER DIAMETER
4.59 FT (1400 MM)

INNER DIAMETER
4.52 FT (1380 MM)

SKIN THICKNESS
0.03 FT (10 MM)

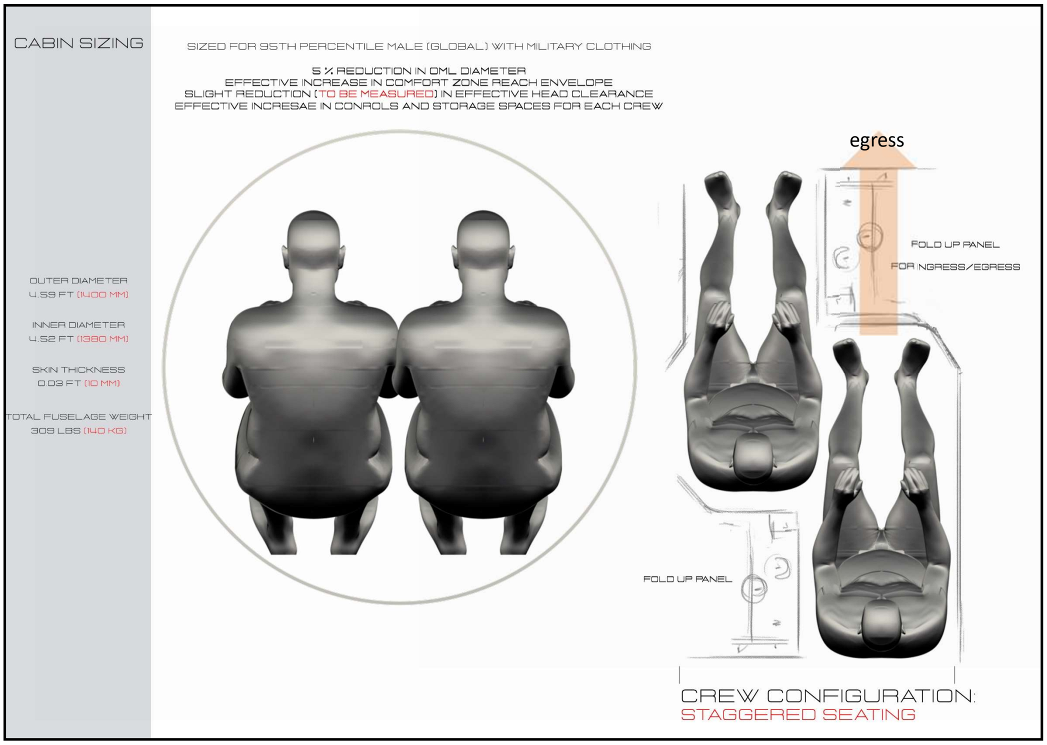
TOTAL FUSELAGE WEIGHT
309 LBS (140 KG)

WAIST WIDTH
16.9 + 1.44 INCHES

SHOULDER WIDTH
20.6 + 1.52 INCHES

25 INCHES
INCLUDING SEAT

CREW CONFIGURATION:
STAGGERED SEATING



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egress

FOLD UP PANEL
FOR INGRESS/EGRESS

FOLD UP PANEL

CREW CONFIGURATION:
STAGGERED SEATING

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Crew Cabin: Pressurized Cabin Volume and Weight

Estimating Aircraft Pressurized Cabin Volume and Weight for Two Occupants

Assumptions

Accommodations for crew in pressurized environment for surface-based operations. Crew seated abreast (for the purpose of initial estimation)

Approach

Estimating pressurized cabin volume and weight based upon historical trends. Comparing the results with available data on previously known prior-art designs. Calculating the pressurized cabin volume and weight from basic principles and comparing the results with those obtained above to arrive at reasonable estimates for preliminary design.

Trends-based Estimation

According to the method discussed by Sforza (2014), we may estimate the cabin volume in terms of the pressurized volume (Vp) and the free volume (Vf). [1]

1. Fuselage Diameter, d (governed by number of passengers seated abreast, Na
2. Cabin Length, l (governed by number of rows, Nr
3. Number of Passengers, $Np = Na \times Nr$

For circular cylindrical pressuirzed sections:

4. Pressurized Volume $Vp = (\pi).l.(d.d) /4$
5. Free Volume $Vf = l.d.h - V0$ (where h is headroom; V0 volume of all equipment inside the cabin)

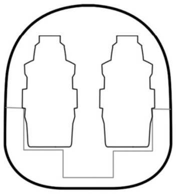

Figure 1: Notional cabin layout showing crew seats abreast

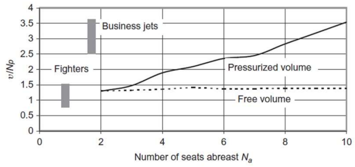

Figure 2: Variation of nominal free and pressurized volume (m3) per passenger as a function of Na for commercial aircraft is shown, with typical ranges for fighter and business aircraft. [2]

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[1] **Sforza, P.M.** *Commercial Airplane Design Principles*
[2] **Sforza, P.M.** *Manned Spacecraft Design Principles*

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It may be drawn from the trends shown above "that when a spacecraft cabin is to accommodate a crew requiring relatively little space for mobility the specific volume may be in the range of 1 to 1.5 cu. m per person."

It is also seen that the pressurized volume is reasonable well correlated by an equation of the form $Vp \sim l.(d.d)$ with the constant of proportonality in the range of 0.25 - 0.6 for dimensions in meters."
The value of 0.25 corresponds to conical shapes and
that of 0.6 to spherical or cylindrical shapes. [2]

For instance when we look at approximations for spacecraft like:

Mercury: length, $l = 2.03$ m
diameter, $d = 2.13$ m [3]
volume parameter: $l.(d.d) = 9.20$ cu. m; $Vp = 0.25\,(l.(d.d)) = 2.3$ cu. m

Gemini: length, $l = 3.36$ m
diameter, $d = 2.3$ m [4]
volume parameter: $l.(d.d) = 17.7$ cu. m; $Vp = 0.25\,(l.(d.d)) = 4.5$ cu. m

Soyuz: length, $l = 2.1$ m (Values for Descent Module)
diameter, $d = 2.2$ m [5]
volume parameter: $l.(d.d) = 10.16$ cu. m; $Vp = 0.60\,(l.(d.d)) = 6.1$ cu. m

The above tally well with the trends shown in Figure 3 and give a sense of approximate values for operational pressurized volumes in spacecraft with one, two and three crews respectively.

In general, the mass constraints imposed on the spacecraft ensure that the gross external dimensions provide a good approximation to the pressurized volume.The free volume figures quoted in the literature are approximately 40%±10% of the pressurized volume. [2]

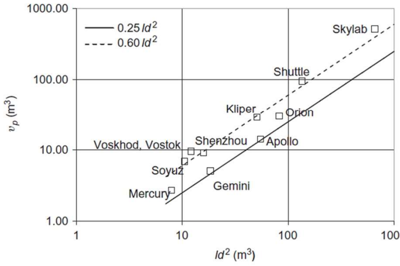

Figure 3: Notional pressurized volumes as a function of volume parameter l.(d.d)

Empirical Estimation

"At the low end of the pressurized volume cases we have,

$Vp = 2 + 0.5.(Np.Np)$" [2]

So for $Np = 2$; we have $Vp = 2 + 0.5.(2.2) = 4$ cu. m

Mass Estimation

The mass of the vehicle scales with two-thirds power of the volume as the vehicle is essentially a pressurized shell structure.

$m = 300\,(l.(d.d))^{(2/3)}$ (Representative of crew compartments of spacecraft like Mercury and Space Shuttle) [2]

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[3] **Baker, D.** *Haynes Owner's Workshop Manual NASA Mercury 1956 - 1963*
[4] **Woods, D.** *Haynes Owner's Workshop Manual NASA Gemini 1965 - 1966*
[5] **Baker, D.** *Haynes Owner's Workshop Manual Soyuz 1967 onwards*

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And based on number of occupants: m = [50.(Np + 1)]^(3/2)
for spherical or cylindrical spacecraft (transportation vehicles) **[2]**

Therefore, m = [50.(2+1)]^(3/2) = 1837.120 kg, gives a working estimate for a pressurized, self-contained crew compartment for the preliminary design of a Mars aircraft

Studying Prior Art Systems for Comparison

Considering the following systems of interest to compare value of overall dimensions and weight for pressurized crew stations:

The General Dynamics F-111 Aardvark used a pressurized crew escape capsule that weighed (3000lb) 1360 kg. **[6]**

The Airbus Perlan II Sailplane uses a pressurized cockpit for a crew of 2. The TGW of the aircraft is (1800lb) 816 kg and it has an empty weight of (1500lb) 680 kg. **[7]**

The above helps establish a range of mass properties for trade studies, bookended at the lower end by the Airbus Perlan II and at the higher end by the empirical result for a space craft obtained earlier.

Calculating Weight of Pressurized Shell from Engineering Principles

Considering the surface conditions on Mars:

The atmospheric pressure on the surface is about less than 1% of the corresponding value on Earth, and is approximately equal to:

P external = 0.088 psi (6.18.e^-5 kg/sq. mm) **[8]**

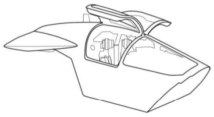

Figure 4: General Dynamics F-111 Aardvark Crew Escape Capsule

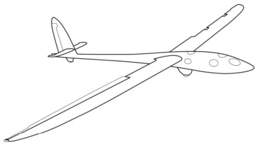

Figure 5: Airbus Perlan II Sailplane, designed to soar at an altitude of 90,000 feet

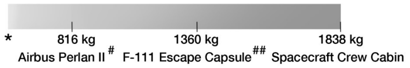

Figure 6: Range of mass propoerties for pressurized cabins for a crew of Two.

* *The actual mass of only the pressurized shell will be lesser than the aircraft TGW.*
\# *The Airbus Perlan II is much lighter as it does not include systems essential for flight on Mars like ECLSS, Radiation Protection, Power Storage to protect the crew*
\## *F-111 Escape Capsule is much heavier as it is part of a system designed to operate at supersonic speeds and withstand ejection forces. It is also largely constructed of mainly metallic materials and represents the state-of-the-art of the 1960s*

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[6] **Escape Capsule:** *https://en.wikipedia.org/wiki/Escape_crew_capsule*
[7] **Windward Performance Perlan II:** *https://en.wikipedia.org/wiki/Windward_Performance_Perlan_II*
[8] **Atmosphere of Mars:** *https://en.wikipedia.org/wiki/Atmosphere_of_Mars*

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Considering Airbus Perlan II Sailplane as a benchmark for value of internal cabin pressure at extreme high altitude we aim for:

P internal = 6.5 psi (0.0045 kg/ sq. mm) = 0.045 MPa **[9]**

Again, considering external dimensions of Soyuz Descent Module as a benchmark for initial estimates due to its high packaging density and good internal volume, we aim for:

Dia outer = 2.2 m (2200 mm),
Raduis inner = 1.1m (1100mm) (assuming thin walled shell structure),
Length outer = 2.1 m (2100 mm) **[5]**

Selecting construction material as Titanium Alloy (Ti6Al4V Grade 5):

Maximum Allowwable Stress, S: 110 MPa **[10]**
Density, p = 4..506 gm/cu. cm (4.506.e^-6 kg/cu, mm)

Weld Joint Efficiency, E = 0.9 (90%)
Corrosion Allowance, CA = 1.5 mm
Thinning Allowance, TA = 0.5 mm

We now calculate wall thickness and weight of a pressure shell for operating under the pressure conditions specified above: **[11]**

$$\text{Shell thickness, ts} = \frac{\text{(P internal).(Radius inner)}}{\text{(S.E) - (0.6.(P internal))}} + \text{CA}$$

$$\text{Therefore, ts} = \frac{(0.045 \times 1100)}{(110 \times 0.9) - (0.6 \times 0.045))} + 1.5 = 0.5 + 1.5 = 2 \text{ mm}$$

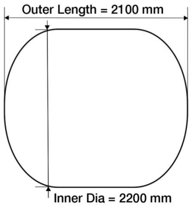

Figure 7: Notional pressure vessel with ellipsoid heads bounding the ends

$$\text{Head thickness, th} = \frac{\text{(0.5).(P internal).((Radius inner + 2.CA))}}{\text{((2.S.E) - (0.2).(P inner))}} + \text{CA} + \text{TA}$$

$$\text{Therefore, th} = \frac{(0.5 \times 0.045) \times (1100 + 2 \times 1.5)}{(2 \times 110 \times 0.9) - (0.2 \times 0.045)} + 1.5 + 0.5$$

$$= 0.25 + 1.5 + 0.5 = 2.25 \text{ mm}$$

Now calculatng the mass propoerties of the pressure vessel: **[12]**

Shell mass, ms = (developed length).(shell length).(density).(thickness)

Also, developed length = (Dia outer - Shell thickness).(π)
= (2200 -2).(3.1416) = 6901.72 mm

Therefore, ms = [6901.72 x 2100 x (4.506.e^-6) x 2] = 130 kg

Head mass, mh = ((1.57).(density).(thickness)).(Dia inner)^2

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[9] **Iturmendi, Miguel A.** *A closer look at the ELSS of the Stratospheric Airbus Perlan II.*
[10] **AZOM Titanium Alloys:** *https://www.azom.com/properties.aspx?ArticleID=1547*
[11] **Livingston, E.; Scavuzzo, R.J.** *Pressure Vessels: The Engineering Handbook*
[12] **Saidpatil, V.V.; Thakare, A.S.** *Design and Weight Optimization of Pressure Vessel due to Thickness using Finite Element Analysis, IJEERT Volume 2 Issue 3 June 2014*

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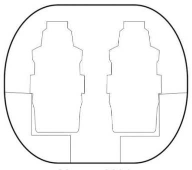
Therefore, mh = (1.57) x (4.506.e^-6) x (2.25) x (2.2)^2 = 77kg

Now, wieght of flanges and other accessories can be approximated as:

Miscellaneous mass, mm = 10% of ms = 0.1 x 130 = 13kg

Therefore Total Mass, mt = ms + 2.mh + mm = 130 + (2 x 77) + 13
= 297 ~ 300 kg

This gives us the estimate of the pressure shell structural mass (dry mass) for the purpose of initial estimates and trade studies.



Mass = 300 kg

Figure 8: Notional pressure vessel fashioned as a crew cabin with structural shell mass (not including any equipment) approximated as 300 kg

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NEXT STEPS:

1. Studying and Sizing the ECLSS for the Pressurized Crew Cabin
2. Trade studies for optimization of Pressurre vessel weight, volume and ECLSS modules sizing
3. CONOPS for MARS Airplane
4. Proposals for Initial Sizing and Concept Designs based on CONOPS

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Step by Step Weight Estimation for the Pressurized Crew Cabin

1. Determine operating pressures for the crew cabin (internal operating pressure of 10.7 psi at 10,000 feet in earth atmosphere).

2. Based upon operating pressures calculate skin thickness required (using ASME codes for design of pressurised vessels).

3. Based upon skin thicknesses obtained, perform weight calculations taking into account material densities to determine weight of thin shells.

4. Check using bursting pressure calculations that the above thickness values are structurally acceptable.

5. Benchmark shell thicknesses used in spacecraft (Apollo) to understand thickness of insulation/secondary structure used.

6. Based upon said values add insulation thickness to shell thickness value and recalculate weight of shell structure for crew cabin.

The insulation and shielding is necessary for the crew cabin to protect them from ambient temperatures and radiation on Mars. Based upon Apollo era figures (0.5 inch to 2.5 inch) it is extrapolated to be 25 mm in wall thickness around the entire cabin for circa 2035. **[14]**

Based upon the above: The total shell weight (including insulation and secondary structure) is estimated to be, Wt = 177 kg or 390 lbs

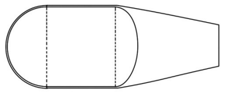

Figure 10: Crew Cabin schematic showing pressurised cabin and unpressurised tapered rear fuselage section.

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[14] Command Module CSM06: *https://www.hq.nasa.gov/alsj/CSM06_Command_Module_Overview_pp39-52.pdf*

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Calculating Weight of Pressurized Crew Compartment based upon Math Data

Crew compartment dimensions:

The pressurized cabin dimensions are:

Cabin length = 7.74 ft (2.359 m)
Cabin width = 4.64 ft (1.414 m)
Cabin height = 4.64 ft (1.414 m)
Wetted area = 113.6 sq. ft (10.553 sq. m)
Cabin volume= 110.9 cu. ft (3.140 cu. m)

The Outer Mold Line (OML) fuselage dimensions are:

Cabin length = 12.26 ft (3.736 m)
Cabin width = 4.84 ft (1.475 m)
Cabin height = 4.84 ft (1.475 m)
Wetted area = 164.1 sq. ft (15.245 sq. m)
Cabin volume= 169.1 cu. ft (4.788 cu. m)

There is a 0.1 ft (0.030 m) gap between the cabin inner wall and the OML for structure and insulation. This can be considered as shell thickness (t) for the pressurized vessel. The front part of the crew cabin is hemispherical in section and the rear part is an isotensoid dome (approximated to the same dimensions as the front part for the purpose of preliminary calculations).

Therefore, weight of the front hemispherical shell can be computed using:
radius outer (ro) = 0.737 m; shell thickness (t) = 0.030 m, as:

Weight Whs = [(4/3)(π).[(ro^3) - ((ro - t)^3)]]/2.material density
= [(4/3)(π).[(0.737^3) - ((0.737 - 0.030)^3)]]/2.(density)
= (0.0982).(density)

Weight of the cylindrical cabin shell can be computed as:
radius outer (ro) = 0.737 m; radius inner (ri) = 0.707 m;
cylindrical length (l) = 0.883 m

Weight Wcs = [(π.(ro^2).l) - (π.(ri^2).l)].material density
= [(π.(0.737^2).0.883) - (π.(0.707^2).0.883)].(density)
= (0.1201).(density)

Weight of the rear isotensoid shell can be approximated as being similar to the front section for preliminary estimates:

Weight Wis = (0.0982).density

Hence total weight can be computed as: Whs + Wcs + Wis
= (0.0982+0.1201+0.0982).(density)
= (0.3166).(density)

Now, consider:
Density of High Performance Carbon Fibers = 1500 - 2000 kg/cu. m
Density of High Performance Titanium Alloys = 4420 kg/cu. m **[13]**

Shell Wall Thickness t = 0.1 ft (0.030 m)

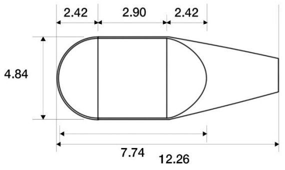

Figure 9: (To be replaced by actual CAD drawing) Fuselage and and Crew Cabin dimensions (not to scale)

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[13] AZOM Carbon Fiber Composites; Titanium Alloys: *https://www.azom.com/properties.aspx?ArticleID=1547*

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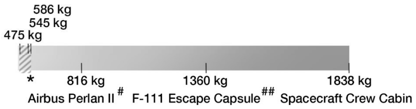
Hence, Total Pressurized Crew Cabin weight can be estimated as:
For complete carbon fibre composite construction: (0.3166).1500 kg/cu. m
= 474.9 ~ 475 kg
For complete titanium alloy construction: (0.3166).4420 kg/cu. m
= 1399.372 ~ 1400 kg
For a more realistic construction with material distribution by weight as:

Ultra-high performance carbon composite:	70%
High performance composites:	25%
Titanium alloy in bulkheads and closure areas:	05%

[(0.3166).(0.70).1500]+[(0.3166).(.25).1800]+[(0.3166).(0.05).4420]
=544.86 ~ 545 kg

For varying degree of metallic construction at 8% and 10% the weight is:
For 8% metallic construction: Weight = 569.75 ~ 570 kg
For 10% metallic construction: Weight = 586.34 ~ 586 kg

Range of mass properties for the pressurized crew cabin of Mars Airplane



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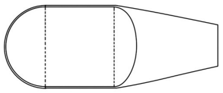

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[14] **Command Module CSM06:** *https://www.hq.nasa.gov/alsj/CSM06_Command_Module_Overview_pp39-52.pdf*