

# Energetic Design and Optimization of a Large Photovoltaic Stratospheric Unconventional Feeder Airship

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## ABSTRACT

This paper presents a model of energetic consumption and photovoltaic production for a large airship which acts as feeder connecting the ground with a large cruiser. The analysis of energy needs and productivity allows defining both an ideal sizing and operative mission profiles. The specialised mission of this airship is to ascent and descent. It includes also the connection with the airport buildings on the ground and with the cruiser at high altitude. Photovoltaic production has evaluated in terms of hydrogen and electric propulsion. They have estimated both and a calculation methodology has proposed. The evaluation has supported by CFD evaluations on aerodynamic behaviour of the system at various altitudes.

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## INTRODUCTION

This paper presents important technical contents of the "cooperative" airship project named MAAT. This acronym stands for Multibody Advanced Airship for Transport. It is a novel airship concept based on the cruiser-feeder architecture.

Photovoltaic and hydrogen productions have evaluated against altitude [1, 2], including energy needs for storage. The productivity for 1 square meter of flat photovoltaic plant has evaluated. It has verified that photovoltaic energy and Hydrogen production increase with altitude.

It has demonstrated that hydrogen prices trends are encouraging the use of hydrogen as buoyant gas, instead of helium, on an economic point of view, even considering photovoltaic hydrogen [3]. It has also verified that a variable volume airship could present large advantages if compared to the constant shape and volume of a traditional airship [4]. It has also shown that an airship with variable volume is safer with Hydrogen than one equipped by ventilated air ballonets [5]. A novel variable volume architecture based on the defined idea has defined. Design guidelines have presented.

This paper defines the energetic balance of a discoid airship with variable volume considering the results of these previous works [6]. This balance considers the atmospheric data and wind velocities at various latitudes and altitudes from U.S. Standard Atmosphere and CIRA Atmosphere models. General mathematical relations which could be applied to define airships behaviour has been obtained by well-known scientific literature [7, 8, 9, 10].

A mostly vertical profile mission of the feeder has been taken into account and a connection model between cruiser and feeder has been defined. Large CFD simulations have been performed to obtain the necessary basis of data to realize the necessary mathematical model that describes the energetic behaviour of the system.

## ATMOSPHERIC DATA

For atmospheric it has been considered two different hypotheses: the use of U.S. Standard Atmosphere model or the use of CIRA Model.

### CIRA Atmospheric Model

The COSPAR International Reference Atmosphere [11, 12, 13] (CIRA) provides empirical models of atmospheric temperatures and densities as recommended by the Committee on Space Research (COSPAR). Since the early sixties, several different editions of CIRA have been published.

CIRA-86 models consists of tables of the monthly mean values of temperature and zonal wind with almost global coverage (80°N - 80°S). They are compiled by Fleming et al. [14](1988), one in pressure coordinates including also the geopotential heights, and one in height coordinates including also the pressure values. These tables were generated from several global data compilations including ground-based and satellite (Nimbus 5, 6, 7) measurements (Oort (1983) [15] and Labitzke et al. [16] (1985)). The lower part was merged with MSIS-86 at 120 km altitude. In general, hydrostatic and

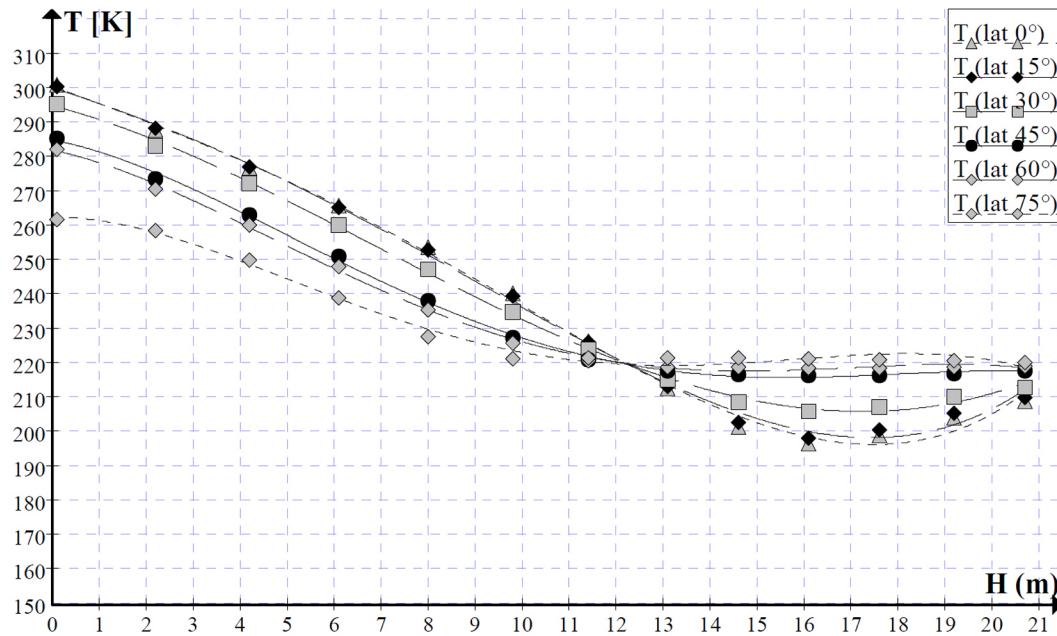


Figure 1. Temperature according CIRA Atmosphere Model.

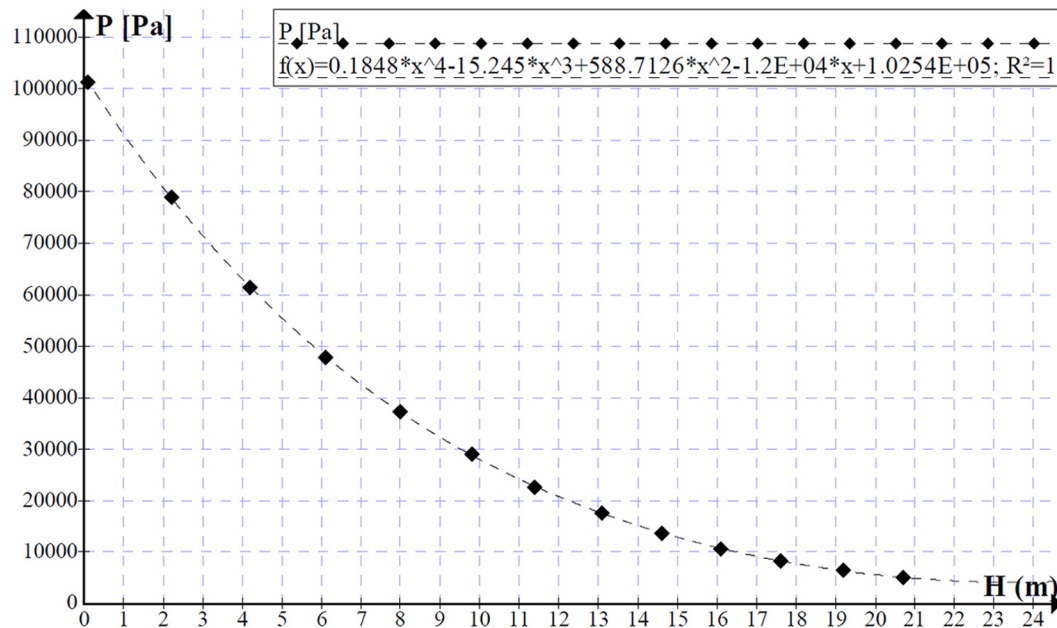


Figure 2. Pressure behaviour according to CIRA Atmosphere and interpolation.

thermal wind balances are maintained at all levels. The model accurately reproduces most of the characteristic features of the atmosphere such as the equatorial wind and the general structure of the tropopause, stratopause, and mesopause.

The CIRA Working Group meets biannually during the COSPAR general assemblies. A global climatology of atmospheric temperature, zonal velocity and geopotential height derived from a combination experimental measurements by satellites, radiosondes and ground-based [17, 18]. The reference atmosphere extends from pole to pole

and 0-120 km. The majority of the data are on a 5° latitude grid and approximately 2 km vertical resolution. This dataset is public.

In particular, it has been compared different values from atmospheric models defining their possible range of validity. CIRA values have been considered. Average Temperature values have been plotted into Figure 1. Average pressure has been plotted into Figure 2. For both data series 4<sup>th</sup> order interpolations has been calculated ( $R > 0.99$ ).

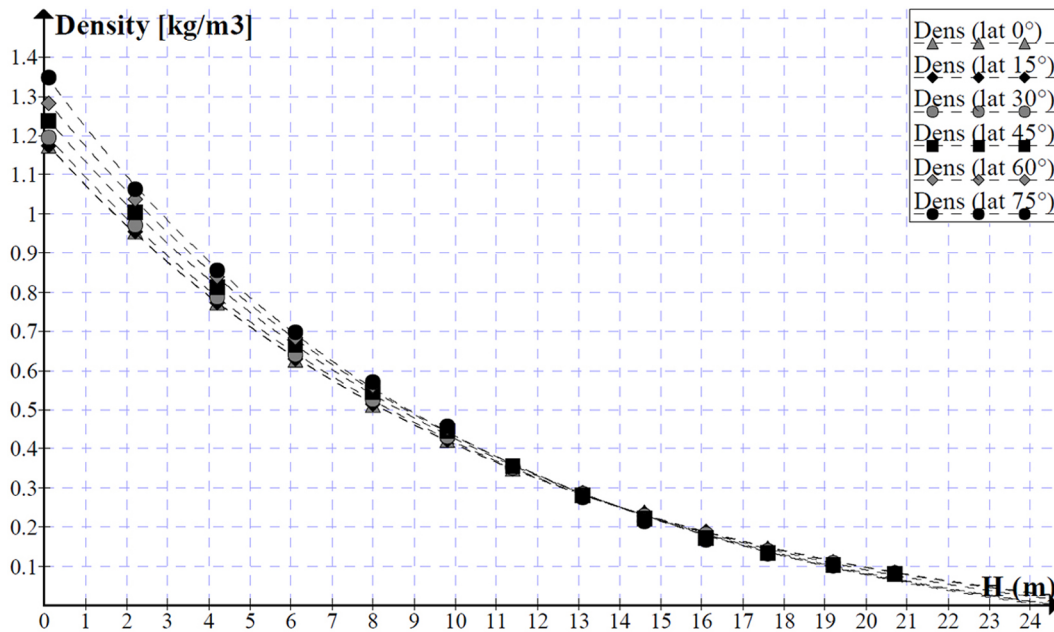


Figure 3. Average local density of air at different latitudes as a function of altitude and interpolating exponential functions

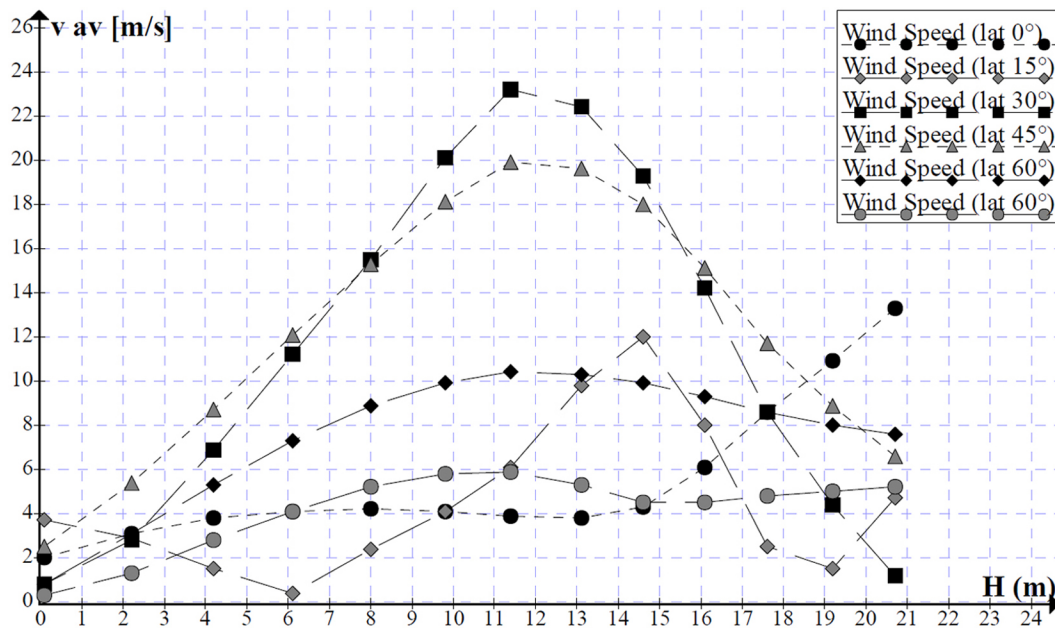


Figure 4. Average annual wind at different latitudes as a function of altitude (North hemisphere)

By the above values, it has been possible to calculate atmospheric densities at various latitudes. They are plotted into [Figure 3](#). Interpolating functions are exponential functions:

$$y = a * \exp(-b H)$$

In addition, wind speeds can be taken into account considering annual average wind speed ([Figure 4](#)) and annual maximum average monthly wind speed ([Figure 5](#)) at most significant latitudes. These values are very important for the further of the definition of the mission energetic profile. This

assumption is done to the extreme variability of the wind values from point to point. It has been assumed because of the extreme geographic variations in the wind velocity.

Even if a mainly vertical mission profile has been evaluated, it can be possible to predict the more calm wind operations. In this case it can be possible to accept different trajectories vertical motion.

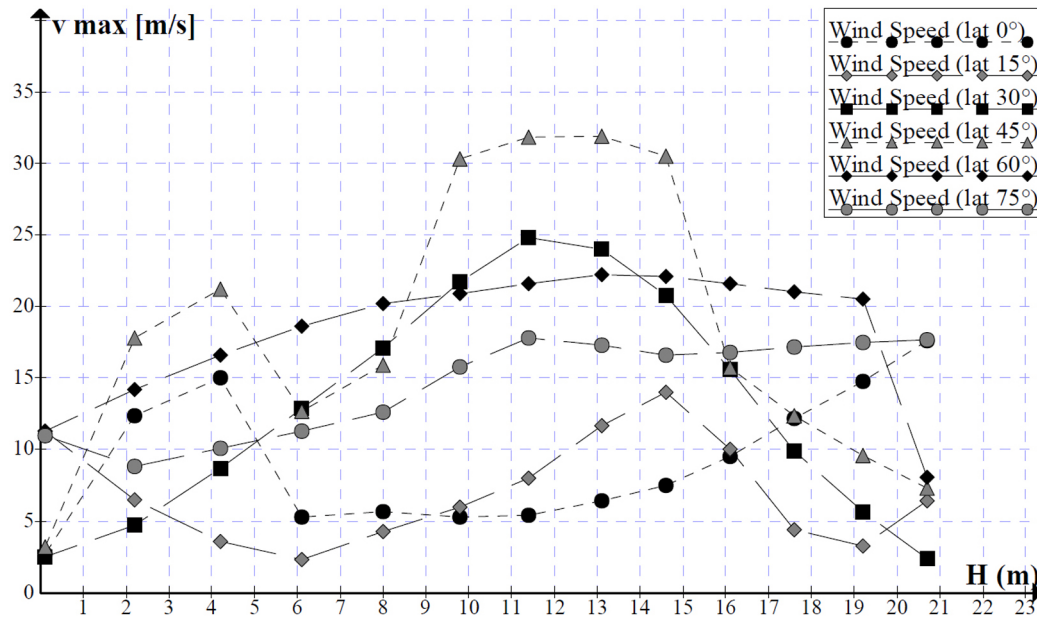


Figure 5. Annual monthly average maximum value at different latitudes as a function of altitude (North Hemisphere)

## U.S. Standard Atmosphere

Some further considerations about atmospheric models can be performed by considering U.S. Standard Atmosphere Model. In particular, it can be verified that Standard Atmosphere Model describes the atmospheric conditions at latitude of 45°. It permits an ease of calculation of most physical parameters but it does not consider wind velocity in its description.

Standard Atmosphere data are reported in the following table (Table 1). The NASA interpolation has been taken into account to simplify the results. Temperature  $T$  and pressure  $p$  can be fitted by the following curves:

$$T = 15.04 - 6.49 \cdot 10^{-3} \cdot H \quad (1)$$

$$p = 101290 \cdot \left( \frac{T}{288.08} \right)^{5.256} \quad (2)$$

The lower stratosphere starts from 11,000 meters to 25,000 meters. To describe the atmospheric models in this region different methods have been created. The simplest is the one proposed by NASA with the following interpolating equations: In the lower stratosphere, the temperature is constant and the pressure decreases exponentially. The metric units curve fits for the lower stratosphere are:

$$T = 329.61K \quad (3)$$

$$p = 22.65 \cdot e^{1.73 - 0.000157 \cdot H} \quad (4)$$

Obtained data are reported in Table 1.

Table 1. Standard Atmosphere Model Calculated Data

| Altitude<br>[km] | Temperature<br>[Kelvin] | Pressure<br>[Pa] | Density<br>[kg/m <sup>3</sup> ] |
|------------------|-------------------------|------------------|---------------------------------|
| 0                | 288.15                  | 101325           | 1.2250                          |
| 1                | 281.65                  | 89875            | 1.1116                          |
| 2                | 275.15                  | 79495            | 1.0065                          |
| 3                | 268.65                  | 70109            | 0.9091                          |
| 4                | 262.15                  | 61640            | 0.8191                          |
| 5                | 255.65                  | 54020            | 0.7361                          |
| 6                | 249.15                  | 47181            | 0.6597                          |
| 7                | 242.65                  | 41061            | 0.5895                          |
| 8                | 236.15                  | 35600            | 0.5252                          |
| 9                | 229.65                  | 30742            | 0.4663                          |
| 10               | 223.15                  | 26436            | 0.4127                          |
| 11               | 216.65                  | 22632            | 0.3639                          |
| 12               | 216.65                  | 19330            | 0.3108                          |
| 13               | 216.65                  | 16510            | 0.2655                          |
| 14               | 216.65                  | 14102            | 0.2268                          |
| 15               | 216.65                  | 12045            | 0.1937                          |
| 16               | 216.65                  | 10287            | 0.1654                          |
| 17               | 216.65                  | 8787             | 0.1413                          |
| 18               | 216.65                  | 7505             | 0.1207                          |
| 19               | 216.65                  | 6410             | 0.1031                          |
| 20               | 216.65                  | 5475             | 0.0880                          |

In conclusion, for the energetic analysis it will be used Standard Atmosphere Model data together with wind data at 45° latitude north for wind speeds.

## DEFINITION OF THE SHAPE

A variable volume shape has been considered for the specific feeder airship. The airship concept is based on the Open Balloon Airship Concept [6] specifically defined to satisfy the most important needs of the MAAT Project [20, 21, 22] (Figure 6). This innovative concept presents an innovative airship concept based on the research of the maximum level of safety for future hydrogen airships.

The ATEN feeder is an airship, which acts as a lifter, for moving people from ground to the Cruiser and from the Cruiser to the ground, where the Cruiser is designed to operate at the stratospheric altitudes. The Open Balloons Architecture (OBA) will be considered as a necessity of the system both (1) to avoid excessive dilatations of balloons, in order to guarantee safety and to ensure an ample possibility to control the buoyancy of the system. This architecture is based on the above presented OBA, and characterized by an intelligent multi balloon system (Figure 7). A top balloon contains the entire necessary gas amount to reach the operative ceiling. A lower balloon can inflate by moving gas from the top balloon to gain altitude.

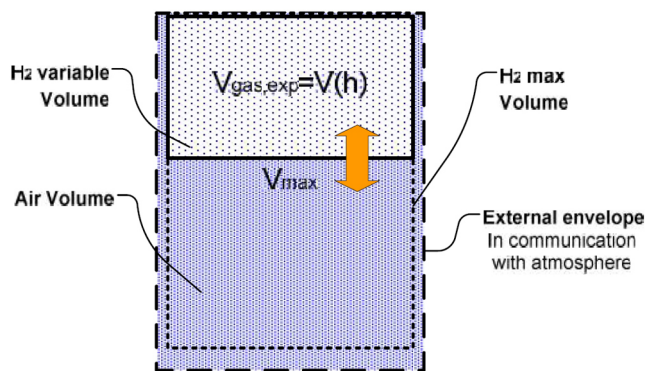


Figure 6. The novel "Open Balloon Airship" Concept

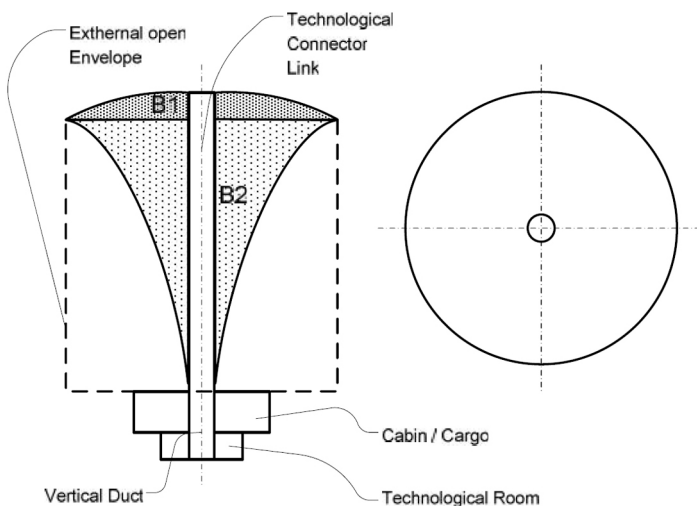


Figure 7. Airship Schematics of the Open Balloon Architecture

This simple concept has been defined into an innovative shape for airship at predominant vertical movement. The volume at different altitudes has been calculated by atmospheric properties, with the hypothesis of an overpressure of the balloon about 5% of the external atmospheric pressure.

The main shape of the airship has preliminarily designed by two hemi ellipsoids of rotation (Figure 8). It has been assumed that a and b axis are equal (diameter of the ellipsoid of rotation) and that  $c_{tot}$  is the sum of the two vertical semi axis. In particular the vertical semi axis of the two hemi ellipsoids are c (fixed), which defines the upper part of the shape, and c' (variable), which defines the lower part of the shape.

By these assumptions, it is possible to calculate the volume of the airship shape by assuming:

$$V = \frac{2}{3} \cdot a^2 \cdot c + \frac{2}{3} \cdot a^2 \cdot c'(H) = \frac{2}{3} \cdot a^2 \cdot [c + c'(H)] \quad (5)$$

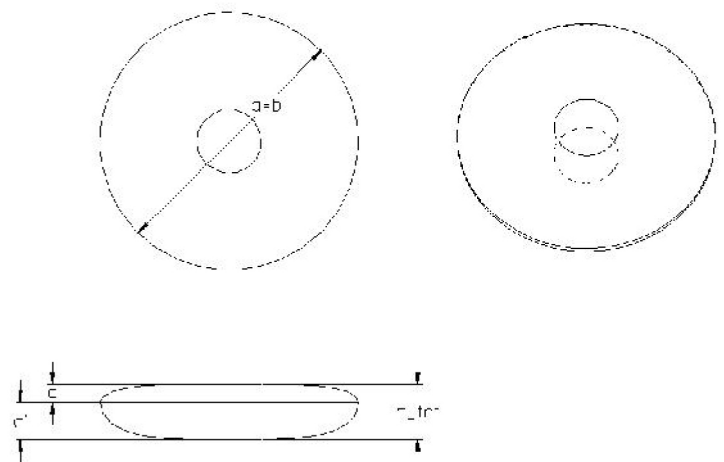


Figure 8. Main Geometric parameters

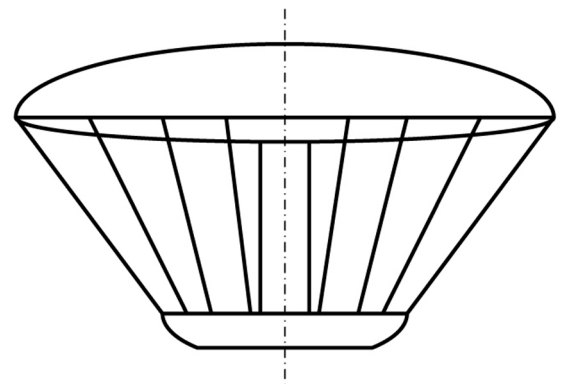


Figure 9. Balloon basic concept

To simplify the cabin positioning and reciprocal connection with the balloon it has been made the hypothesis of a structure formed by a top balloon formed by two hemi ellipsoid sections: the upper has a constant shape and the lower has the possibility to change its own volume. They are connected by an external network of ropes and a thin central column to the lower cabin hosting much of the weight of the system. The lower deformable hemi ellipsoid is governed by ropes which permit that the system can assume the correct volume. The balloon is realized (Figure 9) by two textile elements one which has the function to contain the buoyant gas (hydrogen) and the second with an high porosity which has the function of maintaining the shape together with a funicular structure of flexible ropes.

It has assumed a diameter of 100 m and an overall system weight about 40 tons. It is possible to calculate the following data (Table 2). They are based on the U.S. Standard Atmosphere data and they are reported into Table 1. It has been made the hypothesis to have a certain initial ballast that permit the system to join 4 km altitude without changing its own volume. The ballast is constituted by compressed air which can be simply stored and released with facility. Also water can be taken into account, but the water capture process by air dehumidification presents a more elevated energetic cost and long times, while the system goes down.

Assuming an overall system mass of 40 tons, the following results have been obtained (Table 2). The values designed by the pedicle "th" refer to nominal values, while the ones designated by the pedicle "net" refers by considering 5% overpressure to ensure the possibility to maintain the shape even in presence of elevated winds. The design of the shape at different altitude has been presented into Figure 10.

**Table 2. Physical parameters of the airship and their definition**

| Altitude | Temperature | Pressure | Density              | V theoretical     | V net             | c' theoretical | c' net |
|----------|-------------|----------|----------------------|-------------------|-------------------|----------------|--------|
| [km]     | [Kelvin]    | [Pa]     | [kg/m <sup>3</sup> ] | [m <sup>3</sup> ] | [m <sup>3</sup> ] | [m]            | [m]    |
| 0        | 288.15      | 101325   | 1.2250               | 36317.22          | 39948.9           | 6.0            | 8.7    |
| 1        | 281.65      | 89875    | 1.1116               | 40863.11          | 44949.4           | 6.7            | 8.7    |
| 2        | 275.15      | 79495    | 1.0065               | 42875.67          | 47163.2           | 7.1            | 8.7    |
| 3        | 268.65      | 70109    | 0.9091               | 47467.71          | 52214.5           | 7.8            | 8.7    |
| 4        | 262.15      | 61640    | 0.8191               | 52682.71          | 57951.0           | 8.7            | 8.7    |
| 5        | 255.65      | 54020    | 0.7361               | 58623.83          | 64486.2           | 9.7            | 9.7    |
| 6        | 249.15      | 47181    | 0.6597               | 65414.78          | 71956.3           | 10.8           | 10.8   |
| 7        | 242.65      | 41061    | 0.5895               | 73204.18          | 80524.6           | 12.1           | 12.1   |
| 8        | 236.15      | 35600    | 0.5252               | 82171.67          | 90388.8           | 13.6           | 13.6   |
| 9        | 229.65      | 30742    | 0.4663               | 92535.91          | 101789.5          | 15.3           | 15.3   |
| 10       | 223.15      | 26436    | 0.4127               | 104563.12         | 115019.4          | 17.3           | 17.3   |
| 11       | 216.65      | 22632    | 0.3639               | 118581.49         | 130439.6          | 19.6           | 19.6   |
| 12       | 216.65      | 19330    | 0.3108               | 138835.43         | 152719.0          | 22.9           | 22.9   |
| 13       | 216.65      | 16510    | 0.2655               | 162548.79         | 178803.7          | 26.8           | 26.8   |
| 14       | 216.65      | 14102    | 0.2268               | 190312.56         | 209343.8          | 31.4           | 31.4   |
| 15       | 216.65      | 12045    | 0.1937               | 222817.37         | 245099.1          | 36.8           | 36.8   |
| 16       | 216.65      | 10287    | 0.1654               | 260874.94         | 286962.4          | 43.0           | 43.0   |
| 17       | 216.65      | 8787     | 0.1413               | 305432.37         | 335975.6          | 50.4           | 50.4   |
| 18       | 216.65      | 7505     | 0.1207               | 357601.66         | 393361.8          | 59.0           | 59.0   |
| 19       | 216.65      | 6410     | 0.1031               | 418681.76         | 460549.9          | 69.1           | 69.1   |
| 20       | 216.65      | 5475     | 0.0880               | 490190.62         | 539209.7          | 80.9           | 80.9   |

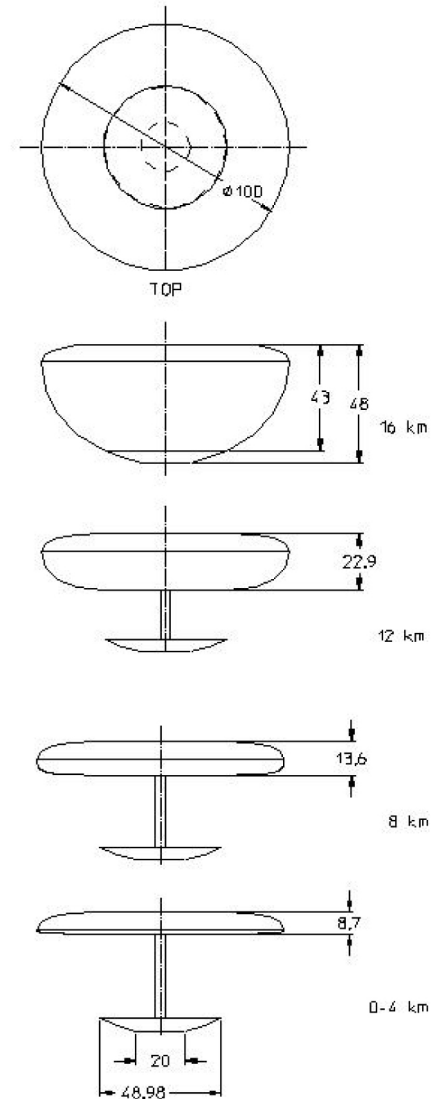


**Figure 10. Feeder geometry at different altitudes.**

## MISSION STATEMENT

The proposed feeder airship has to ensure a good governability in different operating conditions. It has been considered not as an evolution of traditional airships but of aerostatic balloons. To ensure an adequate stability of the system, it is necessary to lower the centre of mass. It has to be lower than the centre of volume of the balloon and the centre of aerodynamic forces. This is a necessary feature which enhances the stability where aerodynamic forces assumes important values. The operative ceiling of the system can be defined about 16 km in the lower stratosphere. To ensure that the volume can remain constant during the operations near the ground up to 4 km, it is necessary to have a well-defined ballast, which has been evaluated in about 12.28 tons.