Design and Analysis of the Pressure Vessel of the Venera Intrepid Lander

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Abstract

This study addresses the design and analysis of the pressure vessel for the Venera Intrepid Tessera Lander (VITaL), a mission aimed at exploring Venus's tessera regions. The challenging Venusian environment, characterized by high temperatures, pressures, and corrosive atmosphere, necessitates a robust pressure vessel. The report employs a literature survey to identify corrosion-resistant materials, selecting Ti-6Al-4V due to its optimal combination of corrosion resistance, strength, and lightweight. The analysis includes thickness calculations, safety factors, and deflection assessments, ensuring the vessel's viability. Despite simplifications, the study concludes that the pressure vessel is well-suited for Venus exploration.

Background and Objectives

In 2010, the National Research Council's Planetary Decadal Survey Inner Planets Panel commissioned Goddard Space Flight Center with developing a Venus mission architecture to safely land in one of Venus's tessera regions [1]. This mission architecture is known as the Venera Intrepid Tessera Lander (VITaL).

The tessera regions of Venus are tectonically deformed regions whose formation process is largely unknown. One theory of the formation consists of a large impact breaking the crust of Venus and creating a melt pond [2]. As the melt rises, it cools to form a crustal plateau above the crust which becomes a tessera. This theory fails to address whether the energy contained in the impact is sufficient to cause the melt pond which forms the tessera.

Interest in the tessera region stems from the fact that tessera regions tend to contain the oldest surface materials[1]. There is a high chance of recovering samples from tessera regions that come from the first 80% of the planet's history, a period of time of which little is known.

The environment of Venus provides many challenges to the design of a vessel. Firstly, the atmosphere of Venus is highly corrosive which greatly limits the potential materials to be used [3]. This is due to the high carbon dioxide content in the atmosphere at 96% carbon dioxide. In addition to atmospheric corrosion, the surface of Venus is a high temperature and high pressure environment. The surface temperature of Venus can reach over 467**°C** with an average pressure of about 92 Earth atmospheres [4]. Due to their altitude, the tessera regions have a slightly different temperature and pressure which are estimated to be about 447**°C** and about 80 Earth atmospheres respectively[1].

The design of the VITaL structure consists of a pressure vessel which houses the measurement instrumentation and electronics of the mission (Fig.1). The pressure vessel is contained in an outer structure consisting of a backshell and a heat shield. The pressure vessel is held in place by a set of inner and outer rings. A drag plate around the pressure vessel assists in the landing of the lander.

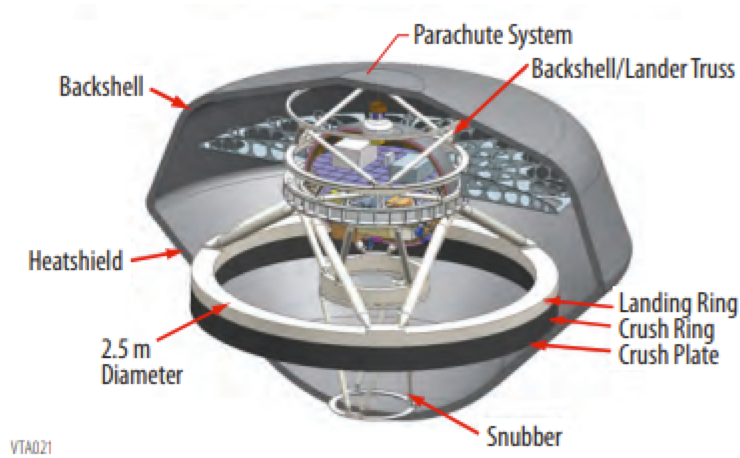

Figure 1. Structure of the VITaL lander. An outside shell with a heat shield covers an internal structure which holds the pressure vessel. The internal structure includes inner and outer support rings as well as a drag plate to assist with landing.

The pressure vessel is essential to this mission given the susceptibility of on-board instruments to the extreme environments [5]. However, the pressure vessel is not well defined within the proposal of the mission. The geometry, dimensions, and materials are provisionally defined or absent from the overall design. As such, the subject of analysis will revolve around broad estimates provided by the proposal, simplifications of geometry for ease of calculation, and conventional aerospace industry standards.

In concept, the proposal outlines the pressure vessel as an oblate spheroid (Fig.2), consisting of three layers: the outer shell, the pressure vessel, and the inner shell. The outer and inner shell serve negligible structural significance but acts as a containment vessel for the insulation material. The exact thickness of these shells is not provided, however, the thickness of the insulation layers, microporous silica insulation and MLI blanket, are provided as 2.2 cm and 2.54 cm thick respectively. From the pressure vessel geometry, there are a number of protrusions defined for use by the avionics and data collecting payload within the pressure vessel. One such protrusion is the cupola, consisting of four window panels for photography and data collection. Other protrusions include the support ring attachments, the atmospheric sampling tubes, and some inner support beams.

Another important structural aspect are the circular, double-paned windows at the bottom of the vessel. The windows have diameters of 6.5 cm, 2.4 cm, and 3 cm respectively and designed for use by the on-board instruments. The proposal suggests the windows are sapphire and double pane to reduce distortion and thermal effects.

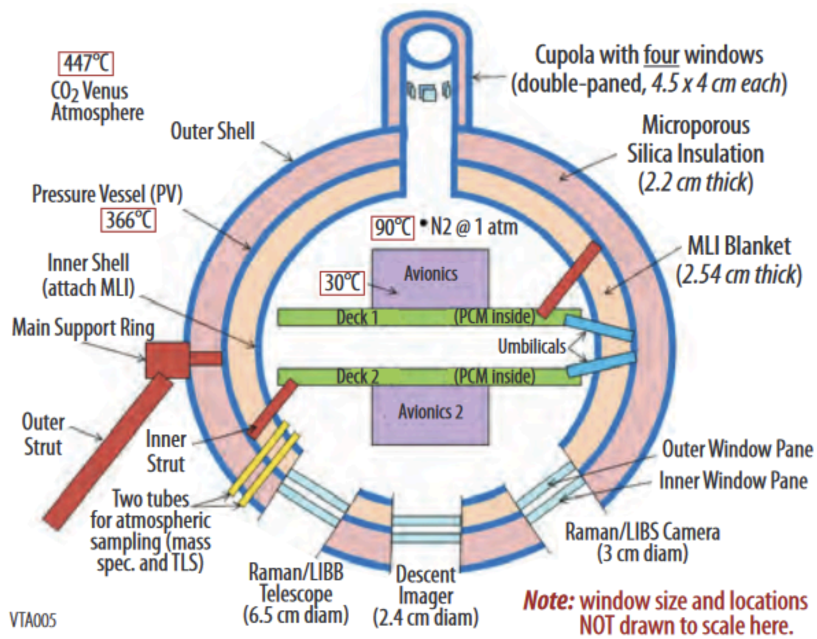

Figure 2. Thermal sketch of lander pressure vessel design [1]. The internal and external environments are shown as well as the general structure of the pressure vessel.

The objective of this report is to design a pressure vessel to withstand the environment of the tessera regions on Venus and to analyze the deformations and stresses on the vessel design. This involves three different areas of design. The first is to select an appropriate material for the pressure vessel which is capable of surviving the corrosive atmosphere of Venus. The second is to design the dimensions of the pressure vessel to support the high pressure and temperature environment of Venus and protect the internal electronics. The third is to design the thickness of the sapphire windows to support the high pressure and temperature environment.

Methods and Analysis

To determine potential materials for the pressure vessel design, a literature survey was conducted on corrosion-resistant materials for use on Venus. A minimum required thickness for each material was determined through a failure analysis on the pressure vessel.

Several simplifications were made for the design of the pressure vessel. The shape of the pressure vessel was simplified to a singular spherical shell. For the analysis of the pressure vessel, the windows were assumed to be negligible. Due to the insulation on either side of the pressure vessel shell, the temperature effects on the pressure vessel were ignored as well. The initial design calculations assumed a thin-walled pressure vessel which was confirmed after the thickness was determined. A safety factor of 1.4 was included as this is a typical safety factor used throughout the aerospace industry[6].

The thickness of the spherical shell for each material was calculated using the thin-walled equation for spherical pressure vessels (Eq.1).

$$t = \frac{(P_i - P_o) \cdot r}{2\sigma_{UCS}}$$

Eq. 1

Where t is the thickness of the spherical shell, P_i is the internal pressure of the pressure vessel, P_o is the external pressure of the pressure vessel, and σ_{UCS} is the ultimate compressive strength of the material. The thickness was then multiplied by the safety factor to determine the final design thickness of the pressure vessel.The pressure vessel was then checked for validity of the thin-walled assumption (Eq.2).

$$\frac{d}{t} > 10$$

Eq. 2

Where d is the diameter of the pressure vessel.

The deflection of each material was calculated for these thicknesses using the thin-walled spherical pressure vessel equation (Eq. 3) [7].

$$u_r = \frac{(P_i - P_o)r^2(1-\nu)}{2Et}$$

Eq. 3

In this equation, u_r is the radial deflection of the shell, ν is the Poisson's ratio of the material, and E is the Young's Modulus of the material. These equations assume that the material is isotropic.

Once the material thicknesses were determined, a material was selected by calculating the total mass of the pressure vessel and choosing the one with the lowest mass to optimize payload and fuel efficiency. The design of the pressure vessel was the required thickness of the chosen material.

Additional simplifications were made for the design of the sapphire window panes. The geometry of the windows were considered to be a thin circular disk with clamped edges. Furthermore, the analysis only covers one pane, rather than the double pane outlined in the proposal. Given the design, the double pane analysis is expected to be equivalent to a single pane design given that they will not fail simultaneously, but instead in quick succession.

The analysis was attempted with the anisotropic nature of sapphire in mind. The stress-strain relation (Eq. 5) of sapphire was approximated given an experimentally sourced [8] stiffness tensor (Eq. 4) (in GPa) and the tensile strength at break.

$$C = \begin{vmatrix} 397.41 & 94.95 & 57.50 & 11.50 & 0 & 0 \\ 94.95 & 397.41 & 57.50 & -11.50 & 0 & 0 \\ 57.50 & 57.50 & 334.36 & 0 & 0 & 0 \\ 11.50 & -11.50 & 0 & 103.46 & 0 & 0 \\ 0 & 0 & 0 & 0 & 103.46 & -11.50 \\ 0 & 0 & 0 & 0 & -11.50 & 151.23 \end{vmatrix}$$

Eq. 4

$$\sigma_{ij} = C_{ijkl} \cdot \varepsilon_{ij}$$

Eq. 5

The derivation of stresses using tensile strength at break assumes that all stresses other than in the radial direction are negligible. From this, strains can be obtained.

The strains can then be integrated to obtain the relevant displacements. However, there is not enough information to obtain compatibility equations. As such, the analysis is redone with an assumption that the material is isotropic.

The displacement of a circular plate is derived (Eq. 6) with the assumption of isotropic material properties [9].

$$w(r) = -\frac{q}{64D}(a^2 - r^2)^2$$

Eq. 6

Where q is the pressure, D is the flexural rigidity (Eq. 7), a is the outer radius, and r is the radial location of the deflection.

$$D = \frac{EH^3}{12\left(1 - \nu^2\right)}$$

Eq. 7

Where H is defined as the thickness of the plate.

A larger radius results in a larger maximal displacement given all else equal. As such, only the largest window of 6.5 cm diameter is analyzed.

To obtain the minimal thickness, the same derived solution is used (Eq. 8).

$$\sigma_{rr}\big|_{z=h,r=a} = \frac{3qa^2}{16h^2} = \frac{3qa^2}{4H^2}$$

Eq. 8

The expected constraining direction is in the radial direction and the maximal stress can be expected where z=h (h is half the thickness H) and r=a (outer edge of plate). From this, the minimal thickness for the 6.5 cm window is obtained. To validate the constraining direction, the tangential minimum thickness is also calculated and is expected to be less than the thickness required by the radial stress.

Results

The literature survey of the material resulted in three potential materials for use in a Venus environment [10]. These materials were Titanium (Ti), Titanium Alloy (Ti-6Al-4V), and Molybdenum (Mo) (Fig.3), all of which are isotropic. The best material for the pressure vessel was found to be Ti64. The minimum thickness of Ti64 was found to be 2.1mm, resulting in a 16.7kg mass which was more than 4 times lighter than the next lightest material of Titanium (Table 1). Material properties were found from online databases [11-13].

Material	Outcome
Ti	Thin surface oxide; no further reaction
Ti-6Al-4 V	Thin surface oxide; no further reaction
Mo	Thin surface sulfide/oxide layers; no further reaction
Cr	Thin layers of sulfide, carbide, and oxide
Co	Co_xS_y crystals
Pd	PdS layers form and peel off
Zr	Porous ZrO_2 throughout sample
Nb	Nb_2O_5 and disintegrates
Ta	Ta_2O_5 layers that flake off
W	WO_3 layers that peel off

Figure 3. Material results of experimental study using simulated Venus atmosphere [10]. The only materials found to have sufficient corrosion resistance were Ti, Ti-6Al-4V, and Mo.

The deflection of Ti-6Al-4V when using the minimum required thickness is -1.5mm which is very large compared to the thickness. As such, the safety factor of the design was increased to account for this (Table 2). With a safety factor of 5 instead of 1.4, the thickness becomes 7.7mm with a deflection of only -0.41mm. Additionally, the mass increases to 58.6kg which is still less than the mass of the other materials at a safety factor of 1.4.

Table 1. Minimum required thickness for different materials to survive Venus environment and resulting deflection and masses. A safety factor of 1.4 was used.

Material	Thickness (mm)	Deflection (mm)	Mass (kg)
Ti	9.5	-0.3	73.1
Ti-6Al-4V	2.1	-1.5	16.7
Mo	4.8	-0.2	84.9

Table 2. Adjusted thickness and deflection values for Ti-6Al-4V for different safety factors.

Safety Factor	Thickness (mm)	Deflection (mm)	Mass (kg)
1.4	2.1	-1.5	16.7
5.0	7.7	-0.4	58.6

With a safety factor of 1.4, the thickness of the largest diameter sapphire window was determined to be roughly 4.8 mm. The tangential minimum thickness is also calculated as 1.3 mm. This confirms the expected constraining coordinate. An approximate deflection for the window is determined to be -0.4 mm at the required thickness.

Other materials could feasibly be explored, particularly given the dated nature of this proposal. However, sapphire fits the directives of the mission along with the specialty use of varying spectrum instruments. As such, sapphire is still a strong material candidate for this mission.

Discussion

Based on the safety factors involved in the design of the pressure vessel and the windows, the pressure vessel is unlikely to fail due to the temperature and pressure environment of Venus. However, there are other factors that were not considered that could cause the pressure vessel to fail.

Despite the corrosion resistance of the Ti-6Al-4V titanium alloy selected for the pressure vessel, it will eventually corrode and become structurally compromised. However, the pressure vessel is expected to last longer than the required mission length of 2 hours. With a thickness of 7.7mm and a corrosion rate of 10 nm over 12 days, the pressure vessel should easily last beyond the mission length.

Another potential source of failure is a landing error. The landing rings are intended to absorb any sources of shock to the pressure vessel, but due to the rough surface of Venus, an improper landing is still possible. This can lead to a puncture in the pressure vessel which is not accounted for in the analysis presented in this report.

Due to the assumptions made in the analysis, the minimum thicknesses calculated are less than the actual minimum thicknesses that would be expected for the design of this pressure vessel. The inclusion of the windows leads to stress concentrators at those areas of the pressure vessel and weakens the pressure vessel. Furthermore, major simplifications were made to the geometry of the overall pressure vessel. Despite this, the pressure vessel is still expected to survive due to the large safety factor involved in the design.

Further analysis can be done using finite element analysis software to confirm the results found in this report. This analysis can be used to further refine the design decisions suggested by the analysis presented.

Conclusion

The environment of Venus presents many challenges in the design of the VITaL lander. The highly corrosive environment greatly limits the potential material options while the high temperature and pressure requires high strength.

The selection of Ti-6Al-4V titanium alloy to be used as the material for the pressure vessel seems to be an excellent choice. Its high corrosion resistance makes it optimal for withstanding the Venus atmosphere and its high strength and low weight allow for a stronger, lighter pressure vessel. In addition, Ti-6Al-4V is already a heavily used material in aerospace applications. These properties make Ti-6Al-4V seem to be an obvious design choice for the pressure vessel.

Sapphire was selected as the preliminary window material in the proposal and exhibits all necessary traits for the mission and its data collection. The high strength and ability to transmit varying bandwidth waves makes the material a strong candidate specifically for use in this mission, given the payload and extreme environment conditions.

This report provides a first order best estimate to the constraints of the lander, its viability, and design requirements. Several simplifications were made in the interest of determining its viability, but more in depth analysis is required to ensure the success of such a mission.

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