PRESSURE VESSEL TECHNOLOGY DEVELOPMENTS
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ABSTRACT

Historically, titanium and aluminum have been used as structural shells or pressure vessels for extreme environment planetary probes and landers. Improvements in the state-of-the-art of pressure vessel materials are sought to reduce the mass of such components by 20 to 50% over titanium shells. The pressure vessel represents the single largest mass element for deep atmospheric probes at Venus, Jupiter and the other Gas and Ice Giants, or landers to the surface of Venus. The high loads on the spacecraft due to atmospheric entry, landing and external atmospheric pressure require high strength structures and new fabrication techniques. Significant improvements to the overall spacecraft design can be realized by reducing the overall mass of the pressure vessel to allow additional payload mass. New structural shell materials exhibit high strength and stiffness at elevated temperatures and are resistant to creep and buckling under high external pressures.

1. INTRODUCTION

The Decadal Survey identified missions to the surface of Venus and the Jupiter Deep Atmospheric Probe as 2 of the 6 highest priority science missions. The present state-of-the-art pressure vessel material, titanium, represents one of single largest mass elements for a Venus Lander or Deep Atmospheric Probe. Given that this material has been used since the early 1970s as the structural shell for these kinds of missions, it is worth examining material improvements over the last 3 decades to see if significant mass reductions can be realized with different shell materials. The pressure vessel for a Venus Lander mission about 1 m diameter would have a mass around 200 kg if it were made of titanium. Using new materials and manufacturing methods, it appears that mass reductions on the order of 50% can be realized over a monolithic (solid metal) titanium shell. However, the Technology Readiness Level (TRL) for these new materials and manufacturing methods as they would apply to a spherical shaped structural shell are typically around TRL 3 even though they may have significant heritage in other applications. Lighter weight pressure vessels impact the whole flight system by reducing the loads carried by the structures within the aeroshell, carrier spacecraft bus and the launch vehicle itself. This is especially significant when designing structures for handling the atmospheric entry loads encountered for missions to Venus or Jupiter which can have decelerations as high as 200 to 300 Gs. This paper describes an investigation into new materials and their associated manufacturing processes for fabricating a spherical shaped pressure vessel (or structural shell) that has potential for use in a space flight mission to the surface of Venus or through the atmosphere of any of the Gas Giant Planets.

2. HISTORICAL PERSPECTIVE

In 1961 the Soviet space agency started an extensive Venus exploration program that eventually included orbiters, atmospheric probes, landers and balloon missions. The program was very successful resulting in many completed missions but it took Soviets many years to learn how to survive and conduct science investigations in Venus environment. In the late seventies NASA conducted a multiprobe mission, Pioneer Venus, aimed at understanding Venus atmosphere.

The Soviet program lasted more than two decades from their first attempt to send a spacecraft to Venus – Venera 1 launched in 1961 to their last mission, VEGA1 and 2, in 1984 which included both a lander and a high altitude balloon on each of two vehicles. The two spacecraft continued to an encounter with Halley's Comet after deployment of their payloads at Venus.

The first spacecraft, Venera 1, had no provision for surviving entry. At that time, Venus was believed to have a much thinner atmosphere and benign temperatures than those we know today. As successive missions were launched they had increasing levels of capability and were equipped to deal with the more severe environmental conditions. In 1965, Venera 3 was the first successful spacecraft to land (by impact) on another planet. However, it was designed to withstand 5 bars external pressure and 80ºC temperature. From 1967 through 1969, Venera 4, 5 and 6 were sent to Venus and were designed to withstand 300ºC and 25 bar. When Venera 5 and 6 were sent, it was known that the surface temperature of Venus was 427ºC and the surface pressure was at least 75 bar. However, it was too late to change the design of those spacecraft. A drawing of the Venera 5 descent module is shown in Fig. 1.

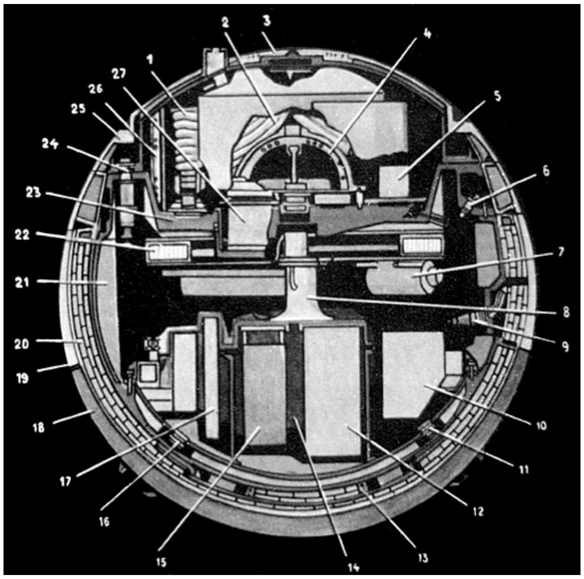

Fig. 1. Venera 5 Descent Module Layout showing all systems were protected by a pressure vessel with passive thermal control.

By 1970, Venera 7 was designed to survive 150 bar and 540ºC and used a titanium spherical pressure vessel. The earlier Venera landers used a hemispherical capsule. This spacecraft successfully survived on the Venus surface for 23 minutes becoming the first spacecraft to transmit from another planet. When Venera 8 was launched in 1972, scientists had accurate estimates of the temperature and pressure environment on Venus. The titanium pressure vessel was designed for surviving 490ºC and 100 bar. It transmitted data from the Venus surface for 50 minutes. A drawing of the Venera 8 descent module layout from [1] is shown in Fig. 2.

The remaining Venera missions 9-14 continued to use the same spherical pressure vessel design criteria as Venera 8, however, they were larger in diameter and were mostly successful missions. Venera 13 and 14 were launched in 1981. The limiting factor in the later missions was communication time with the flyby spacecraft. Fig. 3 shows a photograph of the Venera 13 Lander.

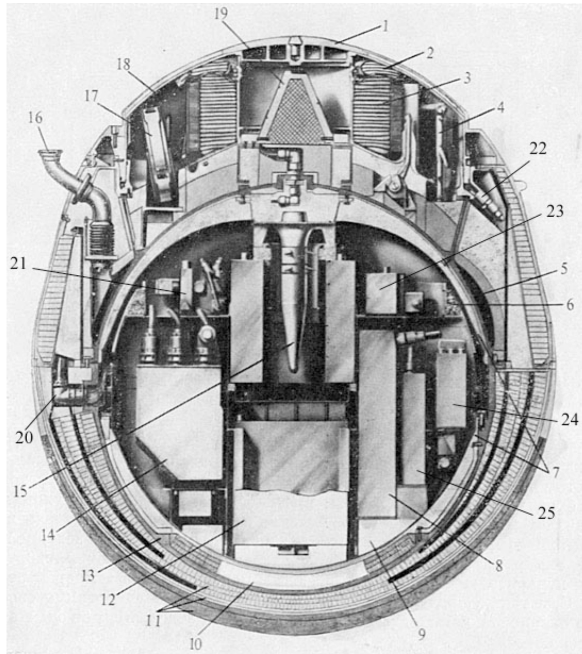

Fig. 2. Venera 8 Descent Module Layout showing the systems packed in a spherical pressure vessel.

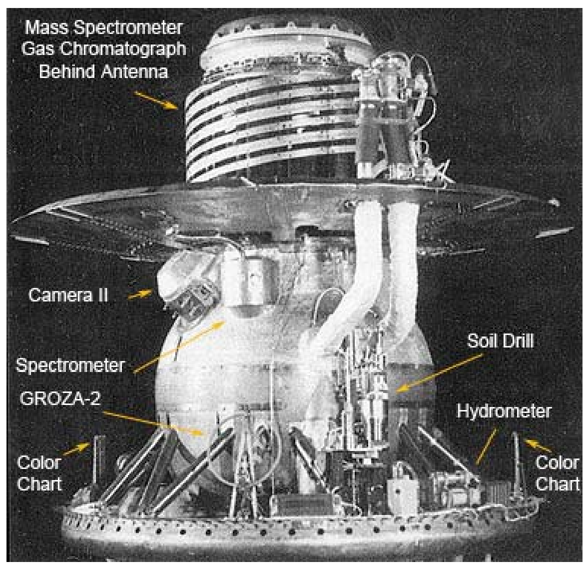

Fig. 3. Venera 13 external configuration photograph.

The only NASA mission to the Venus surface was Pioneer Venus which was launched in 1978. It consisted of one large probe and three small proves. The large probe had a 78 cm diameter titanium pressure vessel while the small probes at 47 cm diameter pressure vessels. Only one of the small proves survived on the surface; none of them were specifically designed to survive landing. Fig. 4 as in [2] and [3] shows an inside view of the Pioneer Large probe.

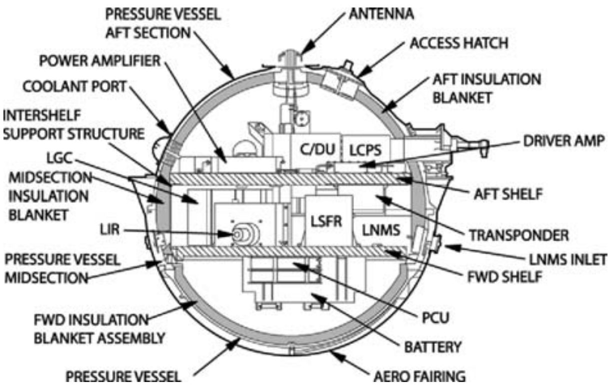

Fig. 4. Pioneer Venus Large Probe interior layout.

A summary of the general development trend in the pressure vessel ratings for missions to the Venus surface is shown in Table 1.

Table 1. Historical Summary of Pressure Vessel Ratings for Venus Landers

Mission	Launch	Pressure Rating
Venera 3	1965	5 bar
Venera 4	1967	20 bar
Venera 5,6	1969	25 bar
Venera 7	1970	150 bar Titanium
Venera 8-14	1972-1981	100 bar Titanium
Pioneer Large Probe	1978	100 bar Titanium
Pioneer Small Probe	1978	100 bar Titanium

PRESSURE VESSEL DESIGN GUIDELINES

A standard set of guidelines was established to compare different pressure vessel materials to one another. Three basic mechanical parameters were used to estimate pressure vessel mass for a given shell diameter. The shell must satisfy these criteria at a temperature of 500ºC: (1) No buckling at the ultimate load of 150 atm pressure using standard NASA knockdown factor of 0.14 for pressure vessels. The common industry standard knockdown factor is 0.30. Knockdown factors account for imperfections in the material and the manufacturing process which deviate from the ideal case. The elastic modulus determines the bucking limit. (2) No yielding at the proof load of 125 atm pressure. The yield strength determines the yield limit. (3) Total allowable creep in 10 hours under 100 atm external load must be less than 0.5%.

These criteria are evaluated based on compressive yield strength, compressive modulus, and creep strain rates. Additional necessary requirements for the pressure vessel material include impermeable to gases and compatibility with the Venus chemical environment. It is also desirable to have low conductivity, however, this requirement can be mitigated against through better insulation. Other factors to be considered in selecting shell materials include: fracture toughness, heat capacity, and thermal expansion coefficient.

Several material candidates were examined to determine their suitability for a spacecraft pressure vessel operating in a Venus environment. These materials were compared to the current state-of-the-art material titanium-6Al-4V. Materials were classified as metallics or composites and are listed below:

Metallic Materials

- Titanium Beta S
- Nickel-chromium alloys: Inconel 718, Inconel X and Haynes 230
- Nickel-chromium-cobalt alloys: Haynes 188
- PH stainless steels: 17-7 PH or 15-5 PH
- Beryllium I-220H

Advanced Composite Materials

- Silicon carbide fiber reinforced titanium matrix
- Boron fiber reinforced titanium matrix
- Inorganic Sialyte based composite
- Aluminum-sapphire carbide metal matrix
- Aluminum-silicon carbide metal matrix
- Epoxy Polymer matrix composite

MATERIAL EVALUATIONS

Inconel 718 showed the best performance in both creep and tensile property comparisons and is the best metallic candidate for a pressure shell using a honeycomb sandwich construction. The high density of nickel alloys prohibits them from being considered for monolithic shell designs. Ti-6Al-4V was the second best performer in the creep and tensile comparisons at temperature. This is the traditional Venus lander spacecraft pressure vessel material and is fabricated in a monolithic shell.

Haynes 188 was originally selected as a candidate because of its superior creep properties at high temperature. However the operating temperature of the pressure shell (500ºC) is not high enough to utilize the creep resistance of Haynes 188. The Haynes 188 alloy (cobalt base) was designed to perform in the 900ºC to 1100ºC range where it is clearly superior to the other materials selected. At 500ºC it is no better than Inconel 718. Haynes 188 was not retained for further consideration.

15-5 PH showed reasonable creep properties at 500ºC, but the creep resistance falls very rapidly in this material above 500ºC leaving little margin. 15-5 PH was not retained for further consideration. Creep data was not available for 17-7 PH. However it is not expected to perform significantly better than 15-5 PH and was not be retained for further consideration.

Beryllium is lightweight and has high elastic modulus, high thermal conductivity and high specific heat but low creep resistance in tension at temperature. Toxicity issues raise concerns regarding fabrication; however established vendors are available to fabricate beryllium products.

In all the metal candidates, bucking was the limiting criteria except for beryllium because of its high elastic modulus. A comparison of elastic modulus as a function of material density at room temperature is shown in Fig. 5 for the metallic candidates. At 500ºC, the magnesium and aluminum alloys drop out of consideration. Beryllium clearly has the highest modulus per unit mass of all candidates even at 500ºC. It is limited by yield and creep.

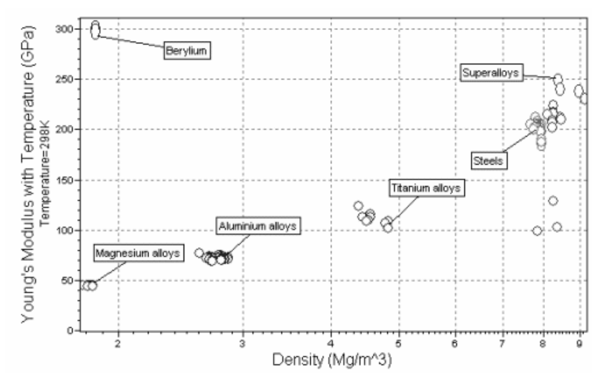

Fig. 5. Modulus comparisons of various metals at room temperature.

SiC/Ti matrix composite has superior strength/density performance compared to other materials. It is creep resistant at 500ºC. It is suitable for fabricating a monolithic shell configuration. Boron fiber titanium matrix composite has good strength to density performance but the boron fibers degrade significantly above 400ºC. It could possibly be used with an external insulation system that would keep the shell temperature below the degradation temperature limit; however it was decided not to pursue this option.

Sialyte is a trademarked inorganic resin product developed by Cornerstone Research Group. The resin is used to fabricate lightweight fiber-reinforced composite structural components. It has a low coefficient of thermal expansion, and relatively high compressive strengths offering consistent performance up to 900ºC. However, it did not have sufficient strength to be considered as a viable candidate for a Venus Lander pressure vessel.

The aluminum-sapphire carbide metal matrix and aluminum-silicon carbide metal matrix are fabricated by passing sapphire-carbide fibers or silicon carbide fibers through a bath of molten aluminum and then wrapped around a mandrel. The process is similar to the method used to make composite pressure cylinders. This allows lightweight tanks to be made without aluminum liners for gas retention. These materials/processes are worth consideration for a Venus Lander pressure vessel but they have not been thoroughly evaluated. The composite material properties are dependent upon the manufacturing technique which needs to be developed for a hemispherical geometry featuring flanges, feed-throughs, ports etc.

An epoxy polymer matrix composite material using the trademarked name Kiboko has been developed by Composite Technology Development Inc. to fabricate lightweight linerless composite wound pressure vessels. It has been primarily developed for storing cryogenic materials or for gases around room temperature. A novel toughened epoxy resin provides the sealing necessary to eliminate the need for a tank liner. Two issues with this material are similar to those above with the aluminum-silicon carbide material: (1) manufacturing a wound product into hemispherical shapes that incorporate many complicating features and (2) performance at high temperatures has not been demonstrated so it may require an exterior insulation system to prevent premature failure.

MANUFACTURING METHODS

Three different pressure vessel configurations have been identified based on the different materials that were considered in this study. Monolithic shells can be fabricated from titanium or beryllium, which has been the traditional manufacturing process for spacecraft landing on Venus' surface. Composite wrapped shells are commonly seen in pressure cylinders and the technology is well developed. This manufacturing technique would be used for aluminum/sapphire or aluminum/silicon carbide or Polymer Matrix Composite materials. Honeycomb sandwich shells are often formed into curved geometries for aircraft engine cowlings for example. This is an appropriate fabrication technique for Beta S titanium or Inconel 718.

Fabricating a monolithic shell for a pressure vessel uses fairly common manufacturing processes. A titanium hemisphere can be shaped using spin forming. Flanges, windows, feed-throughs, brackets etc. can be welded onto the shell to create the spacecraft pressure vessel. An example of a three piece sphere is shown in Fig. 6. A three piece sphere allows two equipment shelves to be mounted to a central ring, while the forward and aft sections of the sphere serve as caps mounted to the center section.

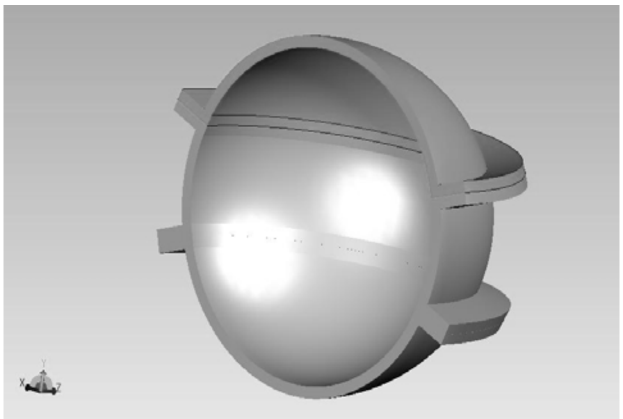

Fig. 6. Cut-Away sectional view of a 3 piece monolithic shell.

Fabricating a monolithic shell out of beryllium can be more difficult than out of titanium. Beryllium is a brittle material and cannot be shaped by spin forming. The spherical sections would have to be machined from solid billets. Flanges and windows etc. cannot be welded to a beryllium shell so these features would have to be machined as part of the shell from the parent billet material. A three piece spherical shell is preferred for beryllium because the billets for each section would be smaller than if it were made into hemispheres. It also would reduce rework costs if mistakes were made during the fabrication process by having to scrap say only 1/3 of the sphere instead of ½ of the sphere. Issues regarding toxicity of beryllium during fabrication processing are of concern and must be dealt with. Also, the vendors qualified to work with beryllium are limited.

Composite wrapped tanks are now commonplace and the latest innovations involve linerless tanks. The impermeable aluminum liner has been replaced by using resins that form a gas-tight barrier which resists microcracking as the pressure cylinder is loaded and unloaded over its lifetime. The manufacturing process consists of passing the wrapping fibers through wet adhesive such as molten aluminum or epoxy. The wetted matrix is then wrapped around a mandrel to form the tank shape. The composite wound tank is then cured at an elevated temperature to set the tank. A picture of composite wound linerless tanks is shown in Fig. 7. While this process is conducive to fabricating pressure cylinders or composite tubes, it has not be used to fabricate hemispherical sections. Thus the manufacturing process for creating a structural shell for a spacecraft with flanges, windows, feed-throughs etc still needs to be developed.

Fig. 7. Linerless composite tanks developed by Composite Technology Development Inc.

Honeycomb sandwich construction produces strong lightweight panels for many applications. While a large majority of honeycomb structures are flat panels, many curved components are fabricated with a honeycomb sandwich construction. To manufacture a spherical shaped segement using honeycomb requires forming the inner and outer facesheets into the desired shape using a bulge-form technique. A picture of a bulge forming tool is shown in Fig. 8. The honeycomb core is made by diffusion bonding thin corrugated sheet (ribbon) sliced to the desired web thickness. The core is then bulge-formed to match the inner and out facesheets. The core is assembled to the facesheets in a special toolset and a braze alloy is added to bond the facesheets to the core. For a titanium structure, TiCuNi braze alloy would be used, while for Inconel the braze alloy would be BNi-8. There are several methods of completing the brazing process, but typically the assembly would be placed in a vacuum braze furnace. A vacuum braze furnace is shown in Fig. 9. When the brazing process is complete, the tool set is removed and the part is ready for attaching features such as windows, flanges, brackets, etc. Adding these components would require cutting the shell for openings and brazing in window ports for example. Flanges and brackets would be brazed on to the shell.

Fig. 8. A typical bulge forming tool for fabricating honeycomb facesheets.

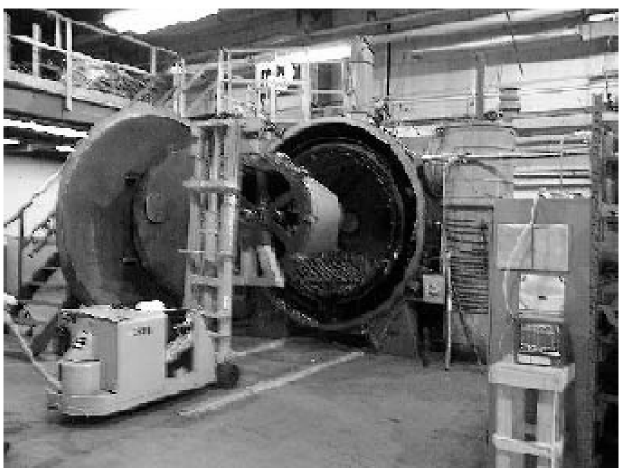

Fig. 9. A vacuum braze furnace for bonding honeycomb structures.

CONCLUSIONS

Development of improve materials and manufacturing methods for fabricating space qualified pressure vessels or structural shells is far from complete. Some of the remaining technology development tasks to improve the current state-of-the-art include: (1) Develop more detailed manufacturing engineering plans for the leading candidate materials. There are many issues involved in fabricating a simple hemispherical shape that can be sealed together with a mating part. Adding features such as optical windows, electrical feedthroughs, flanges, brackets etc. makes the manufacturability of a spacecraft shell even more challenging. (2) Estimate comparative fabrication costs for the different manufacturing technologies. This can help select which technologies are financially feasible to pursue further development. (3) Obtain samples/prototypes of shells from leading candidate materials to demonstrate that the technology is practical. And (4) Perform testing on subscale prototypes under Venus-like environmental conditions for temperature and pressure survivability. The materials and the manufacturing methods examined in this study have the potential for reducing the mass of titanium baseline pressure vessel for a mission to a high pressure/temperature environment by 30 to 50%.

ACKNOWLEDGEMENTS

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