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A Gas management system for an ultra long duration Titan blimp

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Abstract

This paper presents analyses, designs and experimental results for the gas management system of a hydrogen-filled blimp capable of flying in the lower atmosphere of Titan for a period of one year or more. The engineering strategy has two basic elements: first, to minimize leakage rates from the blimp envelope and ballonets; and second, to provide auxiliary subsystems to mitigate the life-limiting effects resulting from those leaks. Leak minimization is achieved through use of cryogenically compatible balloon materials and adhesives, and selection of ballonet geometries that minimize pinhole generation via folding and material fatigue. Hydrogen loss to the environment through leaks in the blimp envelope is compensated for by producing new hydrogen through chemical processing of atmospheric methane. Nitrogen leaked into the blimp from the ballonets is removed by a carbon absorption system and periodically vented to the atmosphere. Data is presented on the measured leak rate from a full scale (13 m long) prototype blimp envelope and on the performance of a low mass, low power prototype device that generates hydrogen from methane. These results are factored in to an overall system design that quantifies the mass and power requirements for a minimum one year operational lifetime.

Keywords: aerobot, balloon, blimp, Titan, mobility

Introduction

Both NASA (APL 2008, Elliott 2007) and ESA (Coustenis 2008) have conducted recent Titan mission studies looking at architectures for future exploration that would follow on the successful Cassini-Huygens mission. In each case, there was explicit endorsement of the idea of using an aerobot (a buoyant mobile vehicle) to fly above the surface and conduct unprecedented in situ exploration over large areas of the world. In addition, there have been several technology development efforts mounted to prepare for such an aerobot mission, details of which and references for can be found in a pair of recently published papers (Hall 2006, 2007).

There are several different alternatives for a Titan aerobot, ranging from a simple, wind-driven balloon that flies at a near constant altitude, to a sophisticated self-propelled blimp that can go to specific sites of interest, vary altitude and acquire surface samples. Inherent to this spectrum of possibilities is the need to choose either a light gas (typically hydrogen or helium) or hot air (Montgolfiere) approach for producing the required buoyancy. The great advantage of hot air balloons is their ability to continue flying even if there are a number of holes in the balloon envelope. This property, when combined with an effectively infinite source of energy from a nuclear power system, offers the possibility of a very long-lived Titan aerobot mission, perhaps measured in years. In contrast, a light gas balloon is very sensitive to leakage of the buoyancy gas: even small pinholes will leak enough gas to limit the mission duration to months instead of years. Therefore, if very long durations are required, then use of a light gas aerobot requires either a leak-free envelope, or some means of supplying additional gas during the flight to compensate for any leakage.

Creation of a leak-free Titan aerobot envelope must be regarded as a daunting prospect. It is true that Mylar superpressure balloons on Earth have flown for up to 744 days, suggesting that effectively leak-free envelopes are feasible. However, there are two aspects of a Titan aerobot mission that greatly complicate achieving leak-free performance. The first is the cryogenic environment at Titan, with temperatures in the range of 80-90 K over the altitudes that the aerobot would fly. Although balloon materials have been developed that can operated at these temperatures, the test data suggests that pinhole creation due to material fatigue occurs much more quickly than seen at Earth-like temperatures. This materials consideration will be described in the next section. The second complication concerns deployment and inflation. On Earth, balloons are prepared and inflated with gas by teams of people that go to great lengths to be careful with the balloon and avoid any damaging contact. Human handling is clearly not possible at Titan: instead, the usual scenario consists of an autonomous aerial deployment and inflation of the aerobot during the initial parachute descent after arrival. The balloon envelope typically experiences significant flexing during this time as a result of the aerodynamic loading during descent, flexing that hastens the creation of pinholes in the cryogenic conditions. As a result of these problems, it seems prudent to pursue a design path that does not rely on leak-free envelopes, but instead uses auxiliary devices to provide additional gas during the mission to compensate for leakage.

This paper describes work that has been done to synthesize an overall gas management solution for a long-lived hydrogen-filled aerobot. A blimp implementation has been chosen so as to bring in the full functionality of not only the hydrogen-filled envelope, but also the atmosphere-filled ballonet required to maintain superpressure during altitude changes. The ballonet introduces an additional leakage problem of atmospheric gas moving into the hydrogen-filled envelope through holes in the ballonet. Therefore, a complete gas management system for a Titan blimp must incorporate one auxiliary device for providing additional hydrogen, and a second device for removing atmospheric gas (mostly nitrogen) from the hydrogen-filled envelope. Figure 1 shows a schematic diagram of this system, one that, in principle, can provide an unlimited float lifetime as long as the leakage rates do not exceed the capabilities of the two auxiliary devices.

A key property of the Titan atmosphere is that it contains approximately 3% methane, which presents an opportunity to create new hydrogen buoyancy gas by chemically processing the methane. Provided that the chemical processing unit (often referred to a reformer) is sufficiently lightweight and low power consuming, it gives a much better solution than the alternative of carrying a high pressure hydrogen gas reservoir. The breakeven point between reformer and reservoir can be estimated as follows. Assume a 1 year period of operation and advanced high pressure composite tank technology that can store 1 kg of hydrogen per 6 kg of tank. Further assume that approximately 10% of the approximately 250 kg total floating mass of the aerobot can be devoted to the hydrogen replacement system, or 25 kg. This gives 3.6 kg of hydrogen stored in 21.4 kg of tanks. The average leak rate is 3.6 kg per 52 weeks, or 69 g per week. Therefore, a hydrogen reformer system that produces approximately this much gas becomes the preferred solution, especially if is has a mass much less than 25 kg and if the desired mission duration is longer than 1 year (as it is). Reformer experiments conducted at Lynntech Inc. show significant progress and indicate that this performance threshold eventually can be met. These results will be summarized later in the paper.

Even with a reformer to produce hydrogen, it is necessary to limit the leakage rate to its ultimate performance, which is likely to be in the range of 50-100 g/week. The next two sections of the paper will discuss the prospects for achieving this low of a leakage rate based on materials testing to date, analogies from terrestrial balloon experience and some thus far limited experiments conducted on a prototype Titan blimp.

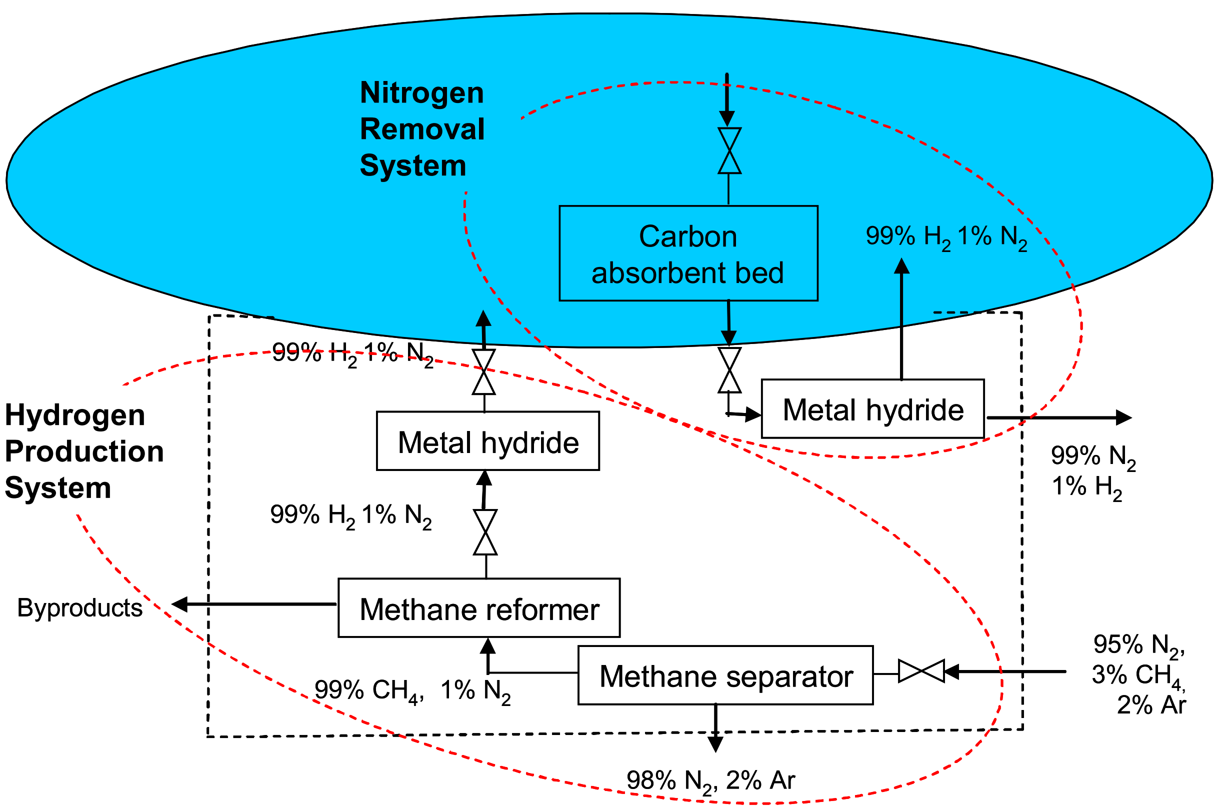

Fig. 1: Schematic of Titan aerobot gas management system

Cryogenic Balloon Materials

Hall (2006) identifies a hexalaminate Mylar film plus polyester fabric laminate material developed by JPL and Lamart Inc. as the best known candidate for a Titan blimp material. This material has an areal density of 94 g/m2 and a tensile strength of 16400 N/m at 77 K. It was selected after an extensive screening process that involved cyclic folding tests at 77 K, tests done with a Gelbo flex tester immersed in liquid nitrogen. In the Gelbo tests, a flat material sample is rolled into a cylindrical geometry, clamped at both ends, then twisted and compressed along the axis to produce severe folding in the sample (Fig. 2). Tests were done at JPL on a large number of samples to quantify how many cycles a material sample could experience before developing a pinhole leak. As can be seen from the selected results presented in Table 1, the hexalaminate Mylar film plus polyester fabric material (94x93 weave, 50 denier) demonstrated amongst the best cyclic loading performance, surviving 2000 cycles before creating a pinhole. A 4.6 m long blimp was constructed from this material and successfully tested at 94 K in a few hour experiment (Fig. 3).

Although high strength is required for the Titan blimp envelope, very little strength is required for the ballonets. However, as can be seen from Table 1, none of the other materials demonstrate significantly better performance on a cyclic loading performance basis than the polyester film plus fabric laminates used for the envelope material. In other words, it does not seem possible to trade off tensile strength for more cycles, at least based on the materials tested thus far at JPL. The conclusion, therefore, is that the ballonet material will start developing pinholes after the first few thousand cycles as well.

Fig. 2: Gelbo flex test

Fig. 3: 4.6 m prototype blimp

Table 1: Selected Results for Titan Balloon Material Gelbo Tests

Material	Vendor	Thickness (μm)	Areal Density (g/m^2)	Maximum cycles without pinholing
Mylar film	Dupont	3.6	5.0	2800
Mylar film	Dupont	8.9	12.5	2400
Mylar film	Dupont	12.2	17.0	2200
Kapton 30HN	Dupont	7.6	11.9	200
Polyethylene Napthalate (PEN) film	Teonix	3.0	5.9	2800
Fiberglass/PTFE (Chemlam Ultra 1100)	Saint Gobain	107	190.0	0
Norlam 1.7 (70 denier polyester fabric + .5 mil Mylar film	Northsail	89	78.0	1000
Mylar bilaminate (2 x 3.6 μm layers glued together)	Lamart	8.9	12.3	3000
Mylar hexalaminate (6 x 3.6 3.6 μm layers glued together)	Lamart	27.9	41.1	3000
Polyester fabric (94x93 weave, 50 denier) plus Mylar hexalaminate	Lamart	99.1	98.0	2000
Nylon fabric (122x80 weave, 30 denier) plus Mylar hexalaminate	Lamart	96.5	83.3	1800

Prototype Blimp Leak Testing

A 13 m long prototype blimp envelope was fabricated from the baseline cryogenic material (Fig. 4). This prototype was inflated with helium and monitored at room temperature for total buoyancy over a 12 day period. The average measured leak rate was 0.88 g per hour, which equals 146 g per week. If the molar leak rate between helium and hydrogen is the same, then this corresponds to a 72 g/week leak rate of hydrogen. This is in the range of the 50-100 g/week rates that we believe will be achievable with a methane reformer system for producing hydrogen, suggesting a first order plausibility that the production and leak rates can be matched. Note that this 13 m prototype included a vent valve on top of the blimp that is believed to not seal perfectly and therefore contributed substantially to the overall measured leak rate. Conversely, this prototype had seen very little handling at the time of the leak measurements and therefore is not representative of the degraded condition to be experienced after months of flight. Therefore, although there is a first order match of leakage to expected hydrogen production rates, confirmation awaits more definitive leak measurements.


Fig. 4: 13 m prototype cryogenic blimp

Hydrogen Reformer Experiments

Benchtop experiments have been conducted by Lynntech Inc. to evaluate the feasibility of developing a low mass, low power reformer system that can produce sufficient hydrogen gas from atmospheric methane at Titan. The complete hydrogen make-up system will consist of a methane enrichment subsystem, the plasma reformer, and a hydrogen separator with hydrogen storage capability. The methane enrichment system consists of a liquid propane scrubber operated in batch mode. A dual use metal hydride ($LaNi_{4.27}Sn_{0.24}$ from Hydrogen Components Inc.) was selected to be employed as the hydrogen separator and hydrogen storage units. The hydrogen reformer is predicated on a non-thermal plasma based methane reformer device.

The complete disassociation of methane, which can be obtained with a thermal plasma, converts a mole of methane into two moles of hydrogen and carbon soot. Although this process results in the highest methane-to-hydrogen efficiency (*i.e.*, methane utilization), the large amount of carbon soot formed is problematic, and the energy efficiency is less than desirable. The equation for this conversion is:

$$CH_4 \Rightarrow C_{(S)} + 2H_2$$

Through the use of a properly tuned non-thermal (non-equilibrium) plasma, the conversion of methane to hydrogen and acetylene is strongly favored over the conversion to soot and hydrogen. The methane to acetylene conversion reaction is then:

$$2CH_4 \Rightarrow C_2H_2 + 3H_2$$

The enthalpy for this reaction is 120.4 kJ/mol H_2, or equivalently a theoretical maximum specific hydrogen production rate of 200.9 grams H_2 per week assuming 20 watts of power consumption. The target hydrogen production rate for this project was 50 g H_2 per week when consuming 20 watts of power, a very aggressive 25% of ideal efficiency.

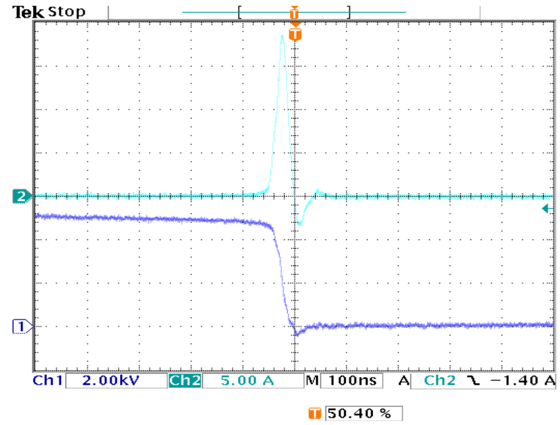

Figure 5: The current pulse and voltage signal. A 5 kV, a19 amp current pulse was created across a 3 mm electrode gap.

The non-thermal hydrogen reformer designed, fabricated and tested by Lynntech consists of two main parts, the pulsed power supply and the plasma reactor. The pulsed power supply was developed in-house at Lynntech and is proprietary. Figure 5 shows the electrical output of the pulsed power supply.

The plasma reactor is a coaxial design with a gap distance of about 2 mm and is shown in Fig. 6. The outer electrode is a bushing inserted on the right side of Fig. 6, and the gap is changed by using different bushings. The reactor was designed with brushes controlled by a stepper motor that provide a periodic, self-cleaning feature. This feature is necessary to address the slow accumulation of carbon soot.

There are several factors that affect the specific hydrogen production rate. Among them are gap length, voltage, frequency, feedstock flow rate, capacitance, and power. Nearly all of these parameters are inter-related. The effect of capacitance (power) on the specific hydrogen production at a methane flow rate of 400 ml/min is shown in Fig. 7. The methane enrichment subsystem mentioned earlier is crucial to this performance since the methane content must be 80 % by volume or greater in order to achieve these levels of specific hydrogen production.

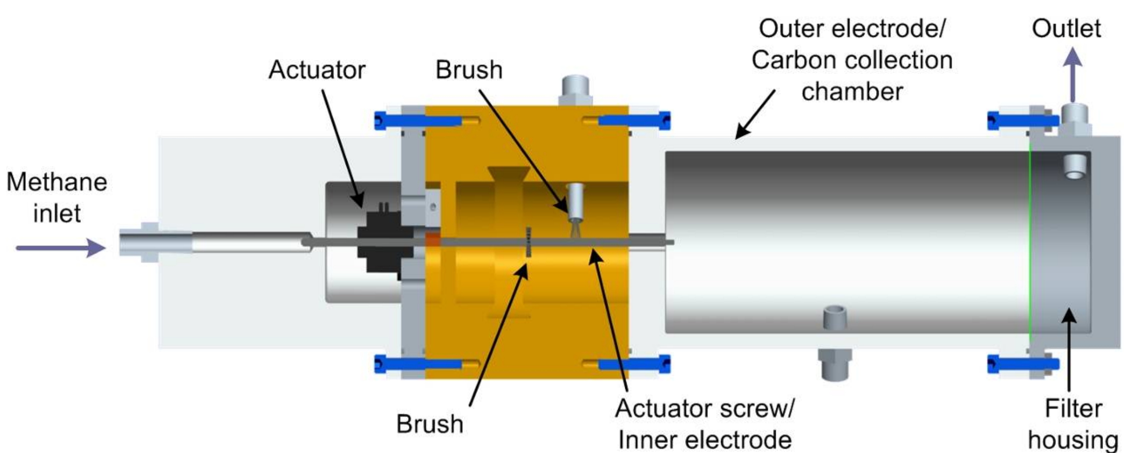

Figure 6: A schematic of the plasma reactor.

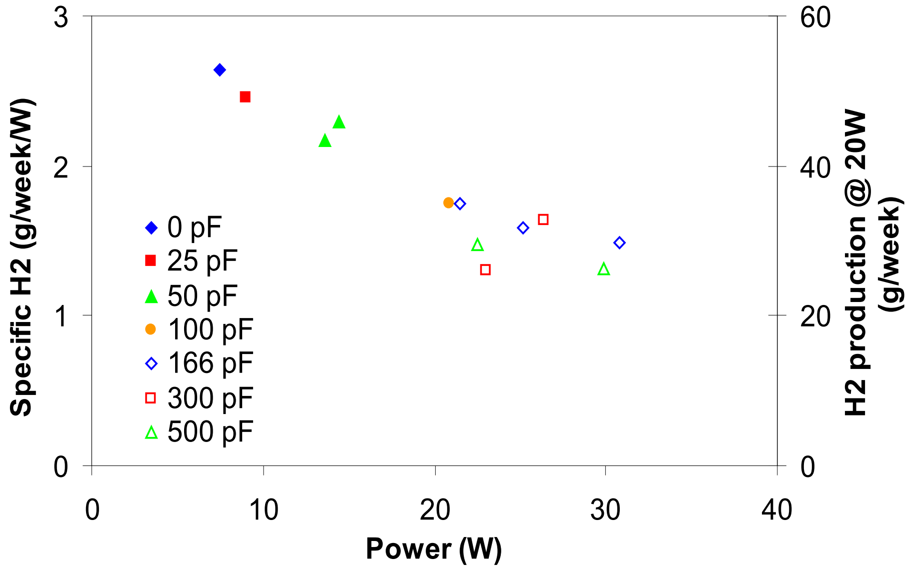

Figure 7: Specific hydrogen production and hydrogen percentage versus capacitance (power) at input methane flow rate of 400 ml/min and a pressure of 10 psig.

The specific hydrogen production increases with decreasing capacitance due to the resulting increase in spark frequency. A few of the better specific production numbers obtained were between 2.5 and 2.7 g/week/watt (50 and 53 g H_2 per week if using 20 W), but the power consumed was only in the range of 7.5 to 9 W. At the lower capacitances, the spark frequency was to be at least 40 kHz. However, the amount of power that can be transferred to the plasma is reduced due to the decrease in the breakdown voltage with increasing spark frequency. Increasing the electrode gap distance would increase the voltage and thus the plasma power. Additionally it should be noted that the Lynntech proprietary-design pulsed power supply used to power the plasma was not optimized for this frequency. It is likely that the power efficiency of the pulsed power supply will increase once it is optimally tuned for the spark frequency that is employed in the plasma reactor.

The overall hydrogen production system contains a few areas that require future effort in order to maximize performance. The two main areas are the methane enrichment subsystem and the non-thermal plasma reformer. The use of propane as a methane scrubber has been shown to be a viable means to enrich the methane to the desired concentrations; however, that process needs to be optimized as far as volume and aspect ratio of liquid propane, flow rate of Titan atmosphere through the unit, and the temperatures of adsorption and desorption cycles.

The non-thermal plasma reformer has met the desired specific hydrogen production numbers, but not at full power of 20 watts. The desired specific hydrogen production rate is currently only obtainable in the 7.5 to 9 watt range. The power can be increased by increasing the electrode gap distance. In this manner the plasma voltage would be increased resulting in a higher plasma power in order to obtain the higher specific hydrogen production at 20 watts of total power consumption. Testing would have to be performed to show that other parameters such as frequency and capacitance are not adversely affected. A second improvement to the plasma reformer can be made to the pulsed power supply. As mentioned earlier, the pulsed power supply is currently not optimally tuned to operate at the desired pulse frequency. Successfully tuning this device will result in a more efficient pulsed power supply and less total power consumption required to achieve 50 g of hydrogen per week.

The discussion above pertains to the subsystem specific testing. Ultimately, the entire hydrogen make-up system would need to be tested. This would include integrating all of the components together and ensuring that each part operated at its optimal point when in the entire system. It is also very important to obtain long-term operation and endurance testing in order to determine what sort of issues arise over twelve to eighteen months of expected operation and how best to address them.

Ballonet Design and Analysis

Ballonets are air-filled bags that are located inside the envelope of an blimp. An Earth blimp typically has two ballonets, one fore and one aft. The ballonets are similar to the ballast tanks on a submarine. Because air is heavier than hydrogen or helium, the ballonets are deflated or inflated with air to affect the trim of the airship, thus helping with ascent or descent. Furthermore, since a blimp is a fixed volume airship, as the blimp descends, the ballonet volumes must expand, and as the blimp ascends, the ballonets must contract, which is the opposite of the helium lifting gas.

Existing terrestrial ballonet designs have evolved to produce stable and predictable forms, and long-lived fabrics. Many aspects of these designs are capable of being translated to potential Titan aerobot ballonet designs, but there are significant limitations which cannot be resolved. The main aspects of the conventional terrestrial designs are outlined below, as the are the limitations for Titan use.

Conventional ballonet designs for terrestrial airships have settled on a relatively simple near-hemispherical form, using a geodesic interface between the ballonet fabric and the hull, in order to ensure minimised fabric area, but avoid localised high stress areas. Such a design involves equal distances across the ballonet skin and the envelope hull at a given position, along a trajectory taken normal to the local profile. A small amount of extra fabric is usually added to the ballonet fabric, to ensure that no local tight spots occur.

The Titan aerobot vehicle design concept requires two ballonets, sized and positioned such that when full, the combined centre of gravity of the two gas masses is vertically coincident with the vehicle centre of buoyancy. In this design, the ballonets can be cross connected, and allowed to fill to a level without changing the vehicle trim. Alternatively, the ballonets may be differentially filled in order to alter the vehicle static trim.

Some initial studies have been carried out into alternative forms, using separate cells which do not intersect with the hull, but these have not been pursued at present, as they require larger fabric areas and so greater weight for a given gas volume contained; they also provide less stable forms when partially filled. Such concepts may have potential advantages in reduced flexing at attachments, and the removal of possibly problematic ballonet to hull intersections, but these are not considered to be sufficient to merit the extra weight and reduced stability. .

Accordingly, the proposed design for the Titan aerobot is conventional, with two near-hemispherical ballonets as used in many terrestrial airships, such as the Skyship series, which have 25 years of flight operation experience to use as a baseline. The Titan aerobot design requirements suggest that a ballonet volume of 30% of total hull volume is appropriate; this is very close to the ballonet percentage of many terrestrial craft (Skyships have 27% ballonets), further reinforcing the similarities, and the validity of the experience base. From this experience, it can be expected that the ballonet fabric will settle into a characteristic primary fold pattern – usually taking the form of a cruciform pattern, with a major fore and aft fold, and a secondary transverse fold. Clearly, the most heavily folded and flexed area of the ballonet fabric is at the cross over of these two primary folds. Other areas of high flexing include the ballonet to hull attachment; this attachment is normally reinforced for structural and constructional reasons.

While the form of the ballonets follows terrestrial precedent and is not expected to provide major design problems, the ballonet fabric itself is considerably more problematic, due to the extreme low temperatures experienced on Titan, at which all candidate materials become stiff, and can expect a very short flex life. Clearly, in any condition other than completely full or completely empty, any movement in the vehicle produces movement of the ballonet fabric which leads to flexing; this in turn leads to flex failure of the fabric, typically in the form of a pinhole leak.

In terrestrial applications, ballonet fabric has been developed to withstand very large numbers of flex cycles at sea level temperatures, typically in excess of 100,000 cycles to formation of a pinhole, and frequently up to 200,000 cycles, as tested by the Bally-Flex test. Whilst there are numerous flex test methods, the Bally-Flex test seems to relate to real ballonet behaviour better than most other tests; in this test, the apex of a double-fold is caused to "walk" along a constant line, thus concentrating the effect of the flexing, and providing the most aggressive but also, experience shows, most representative test. This test has not yet been carried out at Titan temperatures, but the Rotoflex test, a test involving twisting a cylinder of fabric – similar in effect to, but less aggressive than the Bally-Flex test – has been carried out by JPL at liquid nitrogen temperature. In all cases, this has resulted in formation of pinholes after a relatively small number of cycles – less than 3,000 cycles for all the materials tested. When the Bally-Flex test is carried out at low temperature, it is to be expected that the number of cycles to failure will be somewhat reduced compared to the Rotoflex test.

Terrestrial ballonet fabrics are almost universally fine-weave fabrics – usually polyester – with a light polyurethane coating. This type of fabric has required considerable development and optimisation of the coating to achieve high flex life in terrestrial applications. It is only within the last ten years or so that terrestrial ballonet fabrics have achieved the level of performance they now offer. There are numerous examples of promising ballonet fabrics which failed rapidly in service. Work carried out at JPL so far has shown that it is not possible to use this construction for Titan temperature applications; multi-layer film-only polyester materials have proven to provide the best performance. Clearly, considerable work remains to optimise the selected material.

It is difficult to relate terrestrial operational experience to the, as yet unknown, operational requirements of the Titan aerobot. However, some estimates can be made, based on terrestrial experience, and extrapolations to the behaviour of the Titan vehicle can then be made.

There is no direct method to relate flex cycles to operational flying time; however, the flex life of the fabric under test is known, within limits, and the approximate time to ballonet leakage due to pinhole development is also known. The variations in both of these figures are considerable, but they can provide some indications: airships typically start to experience lift gas purity degradation due to ballonet leakage after 1 year of flight operation; aerostats generally show such degradation after 5-6 years operation. This difference is generally due to the smaller number of flight manoeuvres carried out by an aerostat, meaning that a ballonet flexes due to altitude and temperature changes and to a lesser extent due to wind-induced oscillations, whereas an airship experiences variations in pitch and roll attitude due to control inputs, as well as the altitude and temperature effects.

Given the low windspeeds expected on Titan, and the very low thrust and control power available to the aerobot, it is to be expected that the operational requirements for the aerobot are likely to be closer to a terrestrial aerostat than an airship. If some reasonable assumptions are made - 100,000 cycles to significant pinhole generation for terrestrial materials, and 5 years to measurable purity drop – it may be considered that approximately 20,000 flex cycles will occur per year of flight operation. This would mean, with pinhole failure due to flexing at Titan temperatures occurring in around 2,000 cycles, that a Titan aerobot would be expected to develop pinholes capable of causing measurable purity drop in 1/10 of a year, or around 900 hours of flight operation.

It is not possible to predict precise leakage rates from terrestrial operational experience, as operators invariably take action once purity starts to drop – adding clean lift gas, using a gas purifier, and repairing pinholes. Using some very approximate terrestrial assumptions, making no allowance for lowered gas viscosity at Titan temperatures, a leakage rate of around 0.1 litre per hour per pinhole might be expected. This is a very approximate figure, and laboratory tests to establish leakage rates through representative pinholes under Titan conditions would be required, and should be relatively straightforward. Nevertheless, using this value and extrapolating to a time period of 1 year yields a total leakage per pinhole of 876 liters or 0.88 m^3. The size range for a Titan blimp is 50-100 m^3, resulting in a roughly 1% growth in gas volume per year per pinhole. Therefore, a single ballonet pinhole will have negligible effect, while a hundred pinholes will be a serious problem. Given the large surface area of the Titan blimp (order of 100 m^2) it seems much more likely that a large number of pinholes will develop over the course of a 1 year or longer flight. Therefore, unless a breakthrough is made in the design of a material with good low temperature flex properties, it is to be expected that the Titan aerobot will require a system to remove atmospheric nitrogen from the lift gas.

Nitrogen Removal System

To estimate the characteristics of a nitrogen removal system, let us assume a leak of 1 m^3 (1% of the volume of a 100 m^3 blimp) per month, which corresponds to roughly 5 kg of nitrogen per

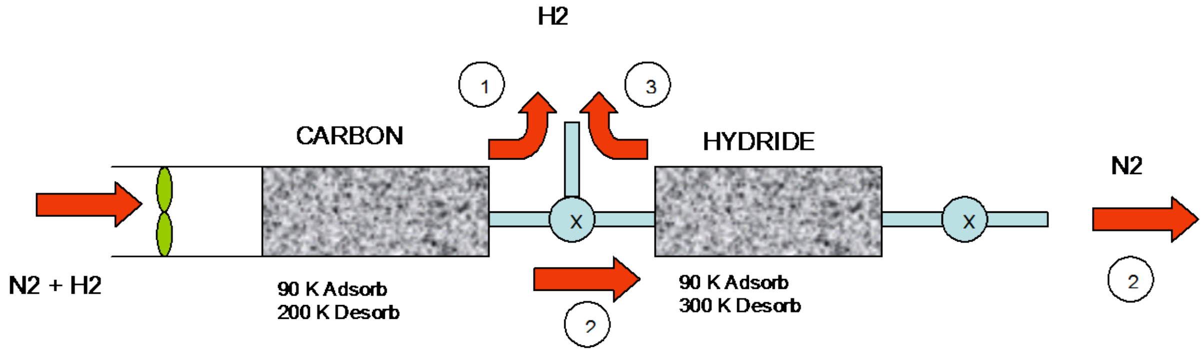

Fig. 8: Candidate Blimp Nitrogen Removal System

month. Given the pinhole leak rate estimated in the last section, this corresponds to 13 pinholes. Removal of this nitrogen requires something that can preferentially absorb nitrogen and not hydrogen. Unfortunately, there are no known, mass-efficient nitrogen chemical absorption getters that do not also absorb hydrogen. Thus, the most mass-efficient means to remove the ambient nitrogen from the hydrogen is to use an activated carbon physical sorbent. At typical ambient Titan temperatures and pressures, e.g. 1 bar at 90 K, activated carbon sorbents (Anderson AX-31M) will adsorb about one gram of nitrogen per gram of carbon, but it will also adsorb up to about 20 mg of hydrogen. For normal operation, a small fan would push the blimp gas through the carbon sorbent and remove the nitrogen (Step 1 in Figure 8). Rather than to throw the adsorbed hydrogen overboard when the carbon sorbent is heated and vented, the desorbed gas would be passed to a hydride bed (Step 2 in Figure 8), which will absorb the hydrogen before venting the nitrogen. The hydride would then be heated to return the hydrogen to the blimp (Step 3 in Figure 8).

The size of the absorbent bed can be minimized by operating the system on a 1 day duty cycle, namely dumping the accumulated nitrogen overboard and reinjecting the hydrogen. The nitrogen absorption per day would therefore be ~ 100 g, requiring about 100 gm of carbon, 400 gm of $LaNi_5$ hydride, plus about 1.5 kg for containers, plumbing, fan, valves, etc. for a total subsystem mass of 2 kg. Total average power requirements will be under about 3 watts. Neither the total mass or power requirement for this nitrogen removal system would be difficult to accommodate on the Titan aerobot.

Conclusions

This paper has described a gas management system that could enable a one year or longer Titan aerobot mission based on light gas (hydrogen) buoyancy generation. The key feature is to include auxiliary devices on the vehicle to compensate for leakage that is expected to occur through both the blimp and envelopes. Hydrogen gas will be created from atmospheric methane and injected into the blimp on a periodic basis to make up for leakage through the envelope. Nitrogen gas will be removed from the aerobot on a periodic basis to remove gas that leaks into the hydrogen reservoir from the ballonets. Preliminary experimental results for cryogenic balloon materials, prototype blimp leak rates and a methane reformer device are promising and suggest that a feasible solution is attainable upon completion of the technology development effort.

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References

APL (2008). “Titan Explorer Flagship Mission Study”, Applied Physics Lab, Johns Hopkins University, NASA 07-05735. Also online at: http://www.lpi.usra.edu/opag/Titan_Explorer_Public_Report.pdf

Coustenis (2008). Coustenis, A., Atreya, S., Balint, T., Brown, R. H., Dougherty, M., Ferri, F., Fulchignoni, M., Gautier, D., Gowen, R., Griffith, C., Gurvits, L., Jaumann, R., Langevin, Y., Leese, M., Lunine, J., McKay, C. P., Moussas, X., Müller-Wodarg, I., Neubauer, F., Owen, T., Raulin, F., Sittler, E., Sohl, F., Sotin, C., Tobie, G., Tokano, T., Turtle, E., Wahlund, J.-E., Waite, H., Baines, K., Blamont, J., Dandouras, I., Krimigis, T., Lellouch, E., Lorenz, R., Morse, A., Porco, C., Hirtizig, M., Saur, J., Coates, A., Spilker, T., Zarnecki, J., and 113 co-authors, 2008. TandEM: Titan and Enceladus mission. *Experimental Astronomy*, in press.

Elliott (2007). Elliott, J. O., Reh, K. and Spilker, T., "Titan Exploration Using a Radioisotopically-Heated Montgolfiere Balloon ", in *Proceedings of Space Technology and Applications International Forum (STAIF-2007)*, M. El-Genk, ed., AIP Conference Proceedings 880, New York, 2007.

Hall (2007). J. L. Hall, J. A. Jones, V. V. Kerzhanovich, T. Lachenmeier, P. Mahr, J. M. Mennella, M. Pauken, G. A. Plett, L. Smith, M. L. Van Luvender, A. H. Yavrouian (2007). “Experimental results for Titan aerobot thermo-mechanical subsystem development”, Advances in Space Research, (in press, available online at http://www.sciencedirect.com/).

Hall (2006). J. L. Hall, V. V. Kerzhanovich, A. H. Yavrouian, J. A. Jones, C.V. White, B. A. Dudik, G. A. Plett, J. Mennella and A. Elfes (2006). “An Aerobot For Global *In Situ* Exploration of Titan”, *Advances in Space Research*, Vol. 37, pp 2108-2119.