

## **Pinhole Effects on Venus Superpressure Balloon Lifetime**

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### **Abstract**

Experimental results are presented for a series of experiments that addressed the effect of small pinhole defects on the potential lifetime of a Venus superpressure balloon. The experiments were performed on samples of a candidate balloon envelope material through which a single small hole of 80 to 300 microns in diameter was deliberately made in each one by puncturing with a metal pin. The material was mounted horizontally in a test apparatus and then a 2-3 mm thick layer of sulfuric acid was placed on top to mimic balloon wetting at Venus. Acid penetration and damage manifested itself as a darkening of the aluminum metal and adhesive layers around the hole in the balloon material. There were no test conditions under which the acid simply fell through the pinhole due to gravity because the surface tension forces always compensated at this size. Very little acid-damaged material was observed for the smallest 80 micron pinholes while gas flowed through the hole due to balloon-like pressurization: the black spot size was approximately 0.2 mm in diameter after 6 days with 86% sulfuric acid. The damage area grew more quickly in the absence of gas flowing out of an 80 micron hole, namely at a rate of 2 mm/day. It was concluded that the flow of escaping gas out of the hole provides a substantial reduction of the rate of acid penetration and damage. Larger diameter pinholes of approximately 300 micron diameter showed larger growth rates of 0.7 mm/day with gas flow and 1.7 mm/day without. The pinhole size did not change over the duration of these experiments because the material has an outer layer of fluoropolymer film that remained intact during the process and thereby held the hole size constant. None of the damage rates measured in these experiments pose a threat to the lifetime of the balloon over the projected course of a 30 day mission because the affected area is too small to cause a structural failure either through direct damage or increased solar heating and attendant balloon pressurization leading to burst.

### **Introduction**

JPL has led a technology development effort in recent years aimed at producing a Venus superpressure balloon that can carry a large payload in the range of 40-120 kg at a 55.5 km altitude for one (Earth) month.<sup>1,2,3</sup> Two 5.5 m prototypes have been constructed (Fig. 1) and tested under a variety of conditions. This includes a successful floating test in the laboratory that exceeded one month of duration without losing all superpressure (Fig. 2). The deduced leakage rate from that experiment was consistent with helium diffusion through the envelope material and demonstrated that there were no pinhole defects through the material.

It has not yet been proven that this particular balloon design will remain free of through-holes after it undergoes the required multi-month trip to Venus in a folded condition followed by an automated deployment and inflation sequence upon arrival in the Venusian atmosphere. The two Soviet VEGA balloons that successfully flew for two days each at Venus in 1985 provide a proof of concept that this kind of storage, deployment and inflation process can be executed without causing pinholes in a balloon envelope.<sup>4,5</sup> Also, no pinholes were created in earlier versions of the JPL Venus balloon material in laboratory tests that evaluated severely folded and wrinkled samples.<sup>2,3</sup> Nevertheless, the possibility of pinhole creation cannot be completely discounted in lieu of further testing on full scale prototypes.

One way to address the issue of robustness of this balloon design prior to such



Fig. 1: 5.5 m diameter Venus prototype balloon undergoing testing in 2008. It used the laminate material described in Fig. 3.

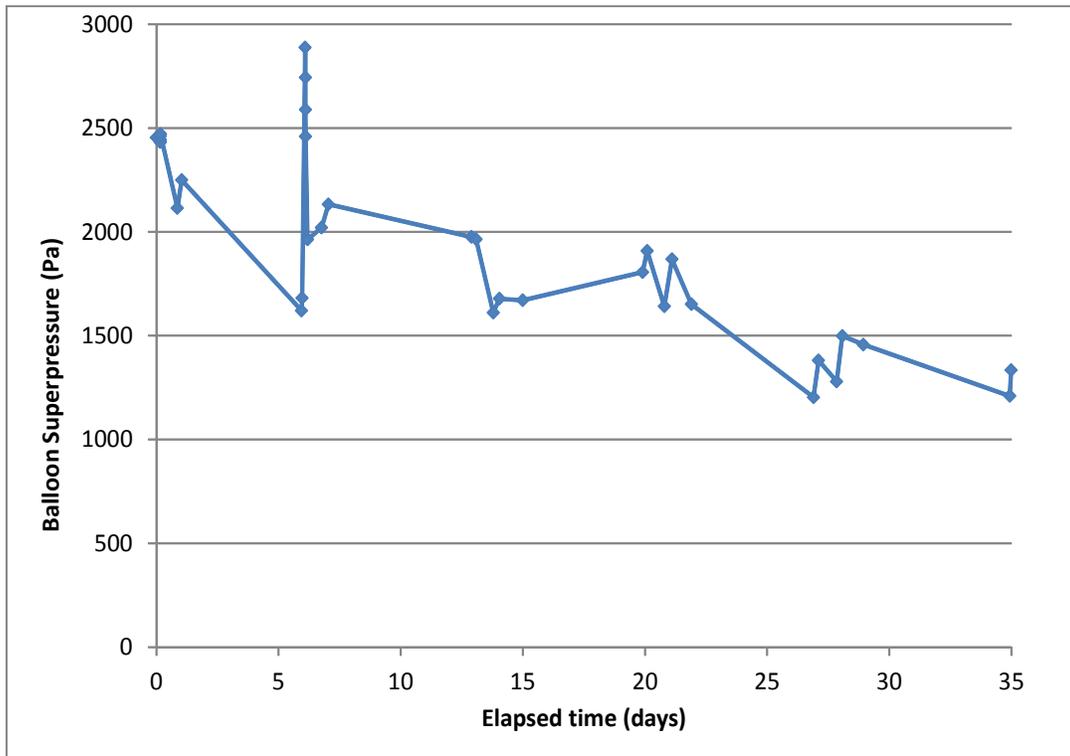


Fig. 2: Venus balloon 35 day buoyancy test data demonstrated pinhole-free performance. Non-smooth data trend reflects small changes in ambient temperature and barometric pressure in the laboratory.

testing is to postulate that the balloon will indeed have one or more pinholes of a specified size and to assess what the effect will be on the balloon floating lifetime. Pinholes can potentially shorten the Venus balloon mission via two mechanisms:

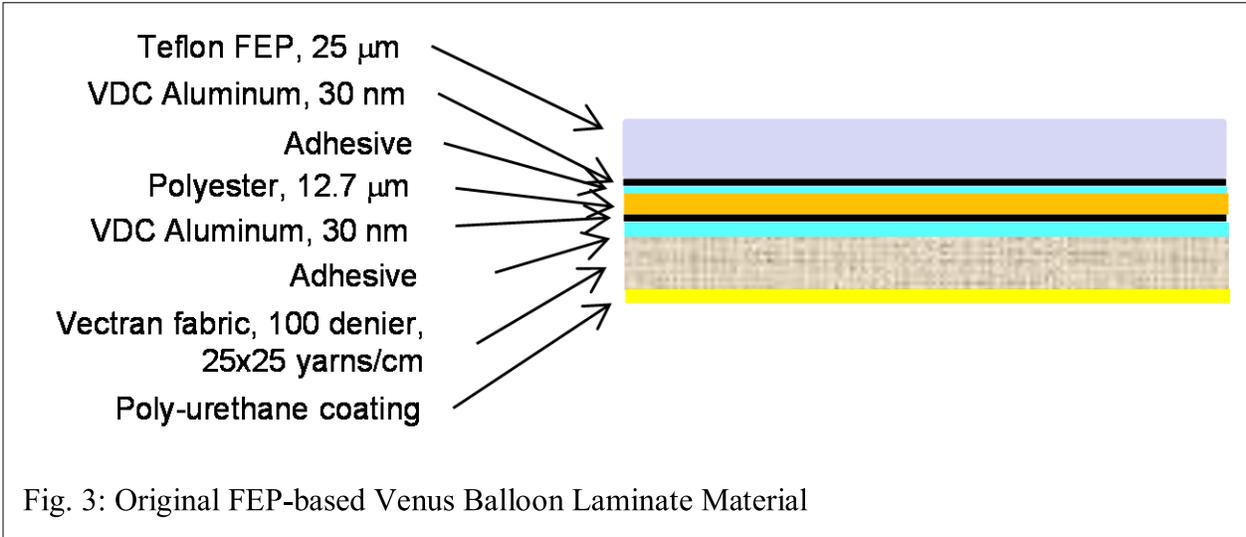
1. The gradual loss of buoyancy gas vented through the hole to the point that the total lift becomes insufficient to float the balloon and payload.
2. Localized structural failure of the balloon envelope due to acid-induced damage resulting in a catastrophic balloon rupture.

Mechanism #1 is present for all balloon missions at all planets. Indeed, there will be a certain size of pinhole, or collection of smaller pinholes adding up to the same cross-sectional area, for which the Venus balloon lifetime will be shortened below the one month mission requirement even in the absence of acid induced structural damage. The next section of this paper presents an estimate of this critical pinhole size for the candidate Venus balloon mission.

The acid-induced structural failure of Mechanism #2 is peculiar to flight at Venus because the clouds are composed of sulfuric acid aerosols with an expected concentration of 85% or higher. The potential for damage results from the fact that not all components of the JPL balloon material are impervious to this acid, and therefore if the outer protective layer is breached, then vulnerable inside components could be damaged. Note that such damage will only occur if acid accumulates on the balloon at the pinhole location due to collisions with and adhesion by sulfuric acid aerosols. It is unclear what is the probability of acid accumulation at a given location under these conditions; however, the VEGA balloons themselves showed little evidence for acid accumulation anywhere on the balloon, as can be seen by the lack of altitude decrease (mass increase due to acid accumulation) for the first 20 hours of the VEGA-1 flight and the first 14 hours of the VEGA-2 flight.<sup>6</sup> Therefore, the scenario explored here is very much a worst case analysis in that it assumes that acid collects at the pinhole location(s) in sufficient quantity to enter the balloon and cause damage.

The JPL balloon material has evolved over the years, although all versions retain a laminate structure with an acid protective outer layer, a metalized layer underneath to reflect sunlight and limit solar heating, and a Vectran fabric for strength. Two versions of the laminate were used in the current acid experiments:

1. The original JPL balloon material (Fig. 3)<sup>3</sup> consisting of:
  - An outside layer of 25.4  $\mu\text{m}$  thick fluorinated ethylene propylene (FEP) film. This film is metalized with a 30 nm vapor deposit coated (VDC) layer of aluminum on the inside surface to reflect sunlight.
  - A layer of 12.7  $\mu\text{m}$  thick polyester film. This serves as the primary barrier to helium permeation through the laminate. This layer is also metalized with a 30 nm VDC layer of aluminum on the inside surface.
  - Vectran fabric composed of 100 denier yarns. This is the strength element of the laminate.
  - A polyurethane coating on the inside Vectran surface. This coating assists with the adhesion of tapes to form gore-to-gore seams in the balloon.
  - Adhesives to connect all of the layers together.
2. The current JPL balloon material (Fig. 4) consisting of:
  - An outer protective layer of 12.7  $\mu\text{m}$  thick perfluoroalkoxy (PFA) film. This is the primary acid barrier.
  - A second layer of 12.7  $\mu\text{m}$  thick perfluoroalkoxy (PFA) film that forms a PFA bilaminate with the first layer for extra acid resistance.

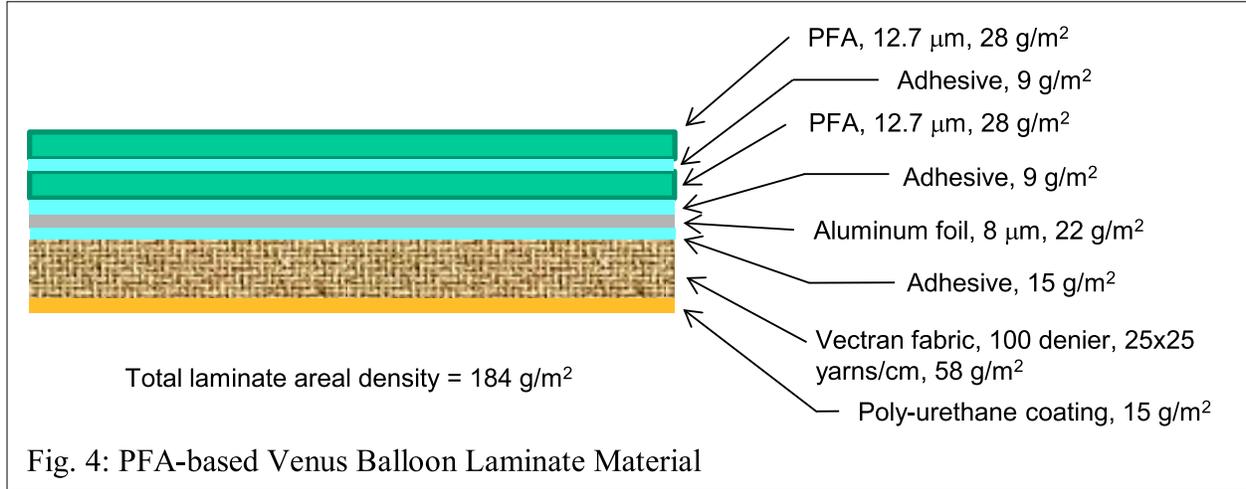


- A layer of 8  $\mu\text{m}$  thick aluminum foil. This serves as both the sunlight reflector and the barrier to helium permeation through the laminate.
- Vectran fabric composed of 100 denier yarns. This is the strength element of the laminate.
- A polyurethane coating on the inside Vectran surface. This coating assists with the adhesion of tapes to form gore-to-gore seams in the balloon.
- Adhesives to connect all of the layers together.

The key differences between the two materials are replacement of the single layer of FEP with two layers of PFA and the use of aluminum foil to reflect sunlight and to provide a superior barrier to helium gas diffusion. Bilamination of the outer protective layer has been adopted into the design to ensure acid protection even if the film has one or more defects.

The PFA and FEP films and the Vectran fabric are tolerant of 85% sulfuric acid, but the other components are not. This allows for the possibility that acid penetrating past the PFA/FEP layer(s) could cause chemical damage to the balloon. This damage can shorten the flight lifetime of the balloon in two distinct ways:

1. The aluminum foil and adhesives will react with the acid and form black spots. These black spots will increase the absorption of sunlight and cause higher internal balloon



temperatures and pressures. If the internal pressure increases too much, the balloon will burst.

2. If the acid penetrates underneath to a load-carrying gore-to-gore taped seam, it could damage that seam to the point that it would no longer support the stress associated with balloon pressurization. The seam would therefore fail and the balloon would suffer a rapid depressurization.

Experiments were performed to assess both potential failure mechanisms. Quite simply, a metal pin was used to deliberately create a pinhole in a sample of balloon material and then the sample was exposed to sulfuric acid under laboratory conditions that mimicked those expected during balloon flight at Venus. The damage caused by the acid was observed over time, allowing for conclusions to be drawn concerning the likely effect on balloon lifetime. Details on the experimental procedure and results are provided later in this paper.

### **Analysis of Leakage Rates**

There is a critical pinhole size below which the balloon can tolerate the accumulated gas loss up to the end of the mission. This critical size was estimated for the planned Venus balloon mission by solving an initial value problem for the thermodynamic behavior of the balloon with the following assumptions:

- 7 m diameter balloon floating at a 55 km altitude at Venus.
- Helium buoyancy gas.
- Starting balloon superpressure (inside-to-outside pressure difference) of 5,000 Pa.
- 30 day mission duration.
- Mission start at nighttime conditions.
- 6 day diurnal cycle with first sunrise at the start of Day 4.
- An estimated 40 K temperature rise of the balloon gas due to maximum solar heating, with a sinusoidal time profile.
- One pinhole located at the very top of the balloon.
- Helium velocity through the pinhole given by  $u = (2\Delta P/\rho)^{1/2}$  where  $\Delta P$  is the sum of the balloon superpressure plus the hydrostatic head inside the balloon and  $\rho$  is the helium density.
- Helium diffusion through the entire surface area of the balloon of 10 cc/m<sup>2</sup>/day/atm. This value was experimentally measured in a sample of the balloon material in Fig. 4.

The results are shown in Fig. 5 as four parametric curves of different pinhole diameters. The diurnal pressure spikes are clearly visible every 6 days and correspond to an additional pressure increase inside the balloon of approximately 7,000 Pa. This pressure rise exacerbates the gas loss due to helium venting through the pinhole. The top line shows the pressure history without any pinholes: clearly, the gas loss from diffusion through the envelope is very small and demonstrates the gas retention effectiveness of the aluminum foil layer. The largest hole shown in Fig. 5, 200 microns in diameter, just barely reaches zero superpressure at the end of Day 24. Although not shown in the figure, a slightly smaller pinhole size of 190 microns does reach the 30 day mark with positive superpressure, indicating that it is the critical pinhole size for this mission concept.

Given these leakage results, the focus of the acid effect investigation clearly needs to be on pinholes smaller than this critical size of 190 microns. Balloons with larger holes will be unable to complete the desired 30 day mission due to helium gas loss alone. The important

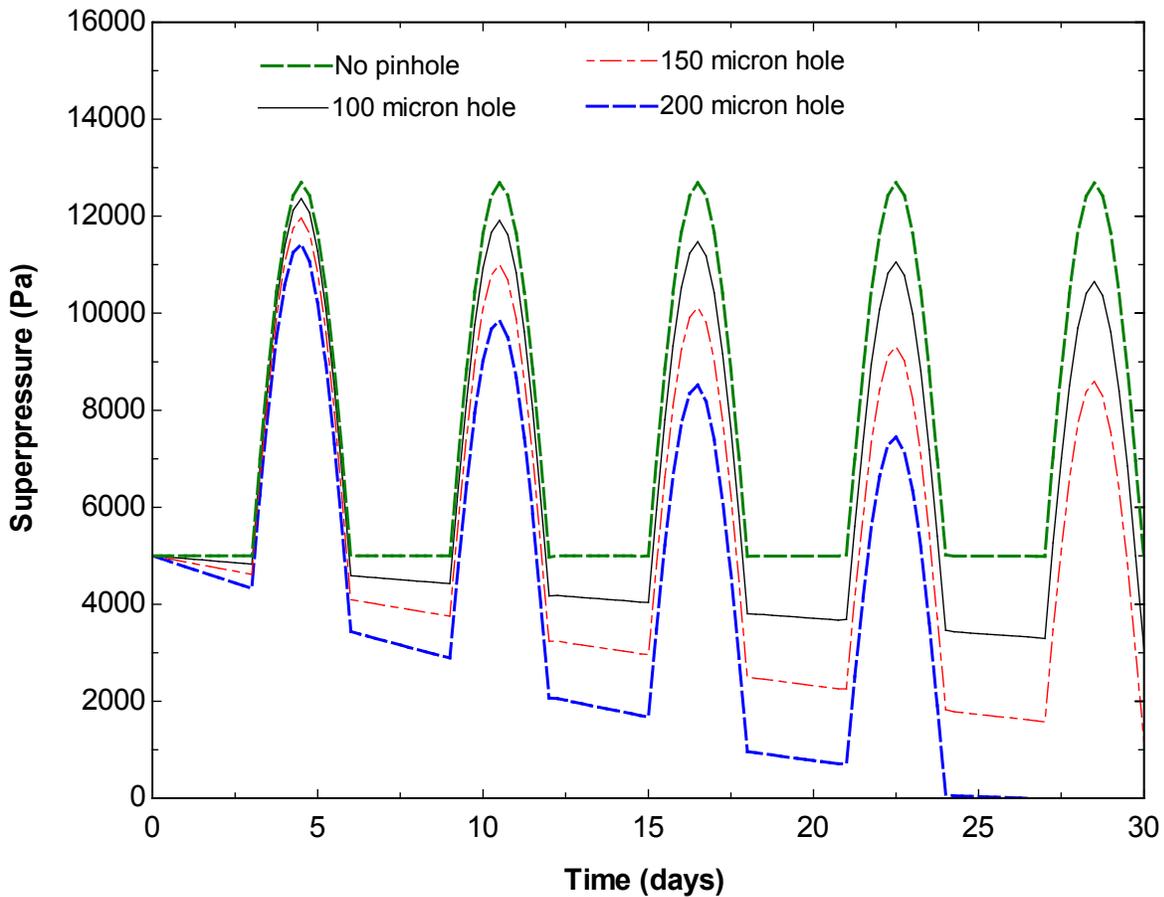


Fig. 5: Analysis results showing balloon pressure loss due to single pinholes of different sizes.

question therefore becomes will acid penetration through smaller holes cause sufficient structural damage to shorten the mission below the 30 day threshold?

### Experimental Apparatus and Procedure

Figure 6 shows the simple apparatus that was put together to do the deliberate pinhole experiments. It consisted of a two-part glass test tube between which was sandwiched a piece of balloon material. The balloon material had a pinhole approximately in the middle of the sample that was created by piercing with a metal pin prior to mounting in the test apparatus. A 2-3 mm thick layer of sulfuric acid was placed on top of the material with an eye dropper. This is certainly more than the thickness of acid that will accumulate on the outside of a Venus balloon due to collisions with aerosols and therefore constitutes a conservative upper limit on the damage potential. Nitrogen gas was used to pressurize the underside of the material to mimic balloon pressurization. In the presence of the pinhole, this pressurization resulted in a small gas flow through the hole and into the top part of the test tube. This gas vented to atmosphere through a desiccant that prevented moisture from entering the apparatus in the opposite direction and diluting the acid. The desiccant is visible in the Fig. 6 photograph as the blue and white granular material inside the foreground glass tube. Figure 7 shows a microscope image of one of the

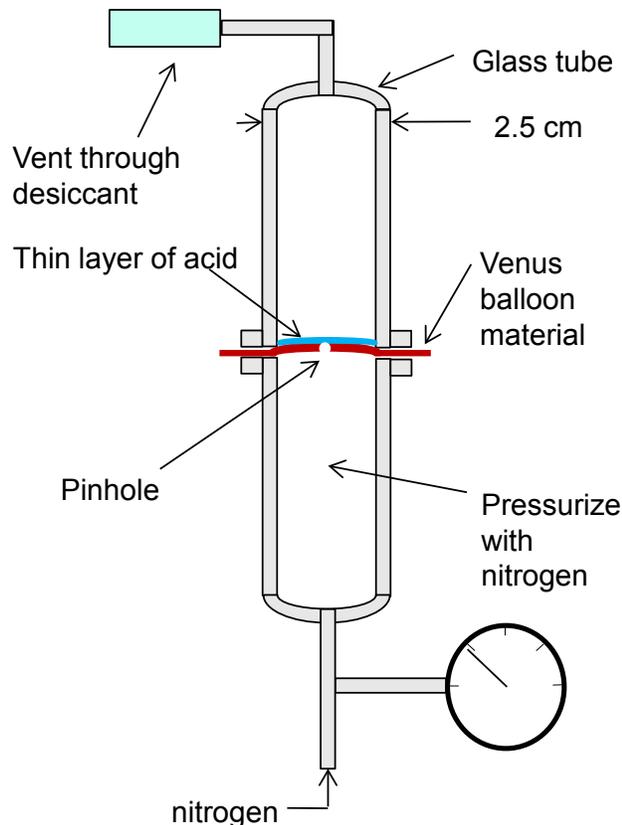


Fig. 6: Experimental Setup

pinholed materials from Test 5, which is representative of all of the samples. The hole is essentially circular with a taper going into the sample. The top surface is the FEP film. Wrinkling caused by the puncture is visible around the perimeter of the hole. Direct measurement just inside of this wrinkled region shows that the diameter was approximately 300 microns, which corresponds to the measured diameter of the pin that was used to make the hole. This hole (and all the others reported below) was generally not visible to the naked eye unless a bright light was placed on one side of the sample in a darkened room. In that case, a pinpoint of light was visible through the pinhole.

### Results and Discussion

A total of 8 material samples were tested in the apparatus described in Fig. 6. Seven utilized the FEP-based laminate (Fig. 3), taken from surplus material left over from the original manufacturing run in 2006. The eighth sample was PFA-based (Fig. 4), taken from a newly manufactured laminate in 2012. The entire test sequence is summarized in Tables 1 and 2 for the FEP and PFA samples respectively. Note that most of the tests are divided into an “a” and a “b” phase: this denotes the same material sample kept in the same apparatus, but subjected to a significant change in the test conditions. These changes are noted in the Tables and generally correspond to a change in and/or stoppage of the gas flow rate.

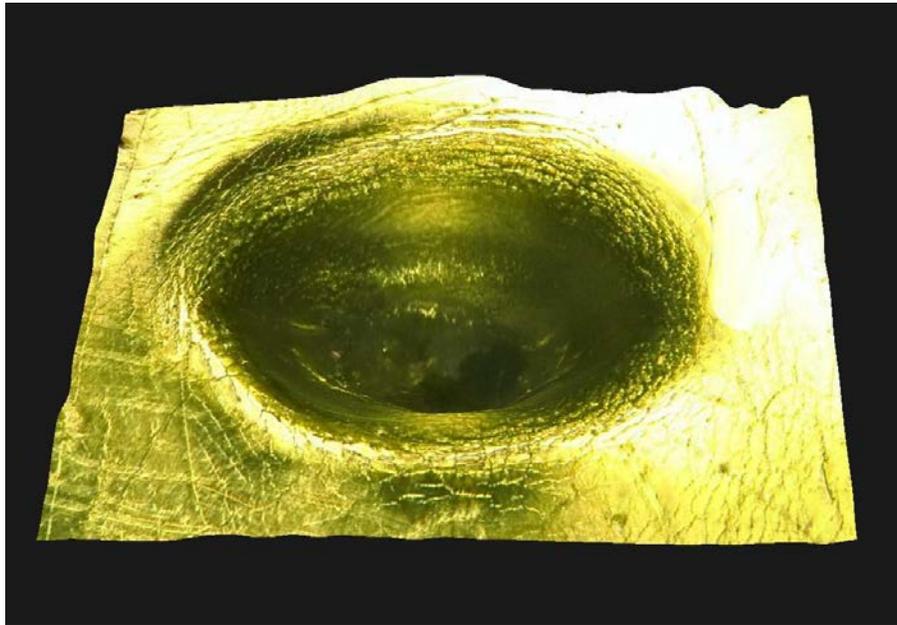


Fig. 7: Microscope Photograph of Pinhole (Test 5 in Table 1)

The three main variables in these experiments were the size of the pinhole, the acid concentration and the presence or absence of nitrogen gas flowing through the hole. Pinhole diameters ranged from 80 to 300 microns, bracketing the critical hole size of 190  $\mu\text{m}$  for which gas loss alone would curtail the 30 day mission. All experiments except #7 were conducted with 86% acid concentration: Test #7 used sulfuric acid with a concentration of 96%. The flow of gas was controlled by means of the pressure setting on the nitrogen gas supply. The pressure in the experiments varied from 0 to 24,000 Pa as noted in Tables 1 and 2. It was observed in all cases that a circular area around the pinhole became black over time. This was taken to be evidence for acid-caused damage, presumably through reaction of the aluminum and adhesive layers underneath the FEP or PFA film. Figure 8 shows a picture of the sample from Test 4 after removal from the apparatus and water washing. The blackened material has been completely removed by water washing leaving a circular “hole” visible in the aluminum layer. The texture of the Vectran threads can be seen throughout the sample and the circular indentation caused by the o-ring seal in the test apparatus can also be seen around the perimeter. The actual 210  $\mu\text{m}$  pinhole is not visible in this image. Column 5 of the summary tables quantifies the growth rate of the damage area in millimeters per day. The test durations ranged from 1 to 13 days as noted in Column 6.

In none of the experiments did the acid simply fall through the pinhole due to gravity, even in the absence of any gas pressure on the bottom side. Surface tension forces are sufficiently strong at this scale to support the weight of the 2-3 mm column of fluid. The acid that does go into the hole attacks the vulnerable elements exposed at the side of the hole, specifically the exposed edges of the aluminum and adhesive layers. These are very thin layers and therefore the damage zone grows very slowly in the radial direction, as can be seen by the low growth rate numbers in Tables 1 and 2. Microscopic observations show that the polyurethane coating in the inside also reacts with the acid and decomposes over a region that

roughly corresponds to the size of the black spot from reacted aluminum and adhesive. There was no evidence that the acid penetrated the pinhole and flowed radially outwards to cover a larger region on the bottom of the material sample than is denoted by the black spot visible from above. The presence or absence of gas flow through the hole makes a large difference in the observed growth rate of the damage area. Experiments 2a, 3a, 7a and 8a all show much smaller growth rates than their counterparts 2b, 3b, 7b and 8b when the gas flow through the hole was stopped. The flow of gas serves to impede the entry of acid into the pinhole, as would be

Table 1: Summary results for FEP-based samples

Test #	Equivalent hole diameter ( $\mu\text{m}$ )	Sulfuric acid concentration	Gas flowing through hole? (Y/N)	Growth rate of damage area (mm/day)	Test Duration (days)	Description
1	80	86	N	0.5	13	Both sides of material vented to the atmosphere.
2a	80	86	Y	<0.1	1	5000 Pa of nitrogen gas pressurization produced a constant stream of bubbles exiting through the acid layer.
2b	80	86	N	0.5	10	This was a continuation of Test 2a but with a ~1 minute interruption of the nitrogen gas pressure at the start. When 5000 Pa of pressure was re-applied, no gas flow was observed.
3a	80	86	Y	<0.1	6	Damage area was 0.2 mm after 6 days. 16,000 Pa of nitrogen gas pressurization produced a constant stream of bubbles exiting through the acid layer. On Day 6 the pressure was reduced to 6000 Pa at which point the bubbles stopped.
3b	80	86	N	2	2	This was a continuation of Test 3a but with no gas pressure applied. Instead the material sample was vented to the atmosphere.
4	210	86	Y	0.8	6	8000 Pa of nitrogen gas pressurization produced a constant stream of bubbles exiting through the acid layer.
5	300	86	Y	0.7	7	8000 Pa of nitrogen gas pressurization produced a constant stream of bubbles exiting through the acid layer.
6	300	86	N	1.7	7	No gas pressurization, no gas flow through hole, material was vented to the atmosphere.
7a	80	96	Y	0.3	5	8000 Pa of nitrogen gas pressurization produced a constant stream of bubbles exiting through the acid layer. Higher acid concentration.
7b	80	96	N	10	1	This was a continuation of Test 7a in which the gas pressure was removed and hence no gas flow through the hole.

Table 2: Summary results for PFA-based samples

Test #	Equivalent hole diameter (μm)	Sulfuric acid concentration	Gas flowing through hole? (Y/N)	Growth rate of damage area (mm/day)	Test Duration (days)	Description
8a	80	86	Y	<0.1	2	24,000 Pa of gas pressurization produced bubbles through the acid layer. Bubbles stopped when gas pressure was reduced below 9,000 Pa.
8b	80	86	N	2	2	This was a continuation of Test 1a in which the gas pressure was removed and hence no gas flow through the hole.

intuitively expected. The protection is not perfect, however, because black spots are observed to grow in all cases, albeit at very small rates.

Note that merely pressurizing the backside of the material did not necessarily cause gas to flow through the pinhole. For example, the transition from Experiment 2a to 2b consisted of a 1 minute interruption of the gas flow. Prior to the interruption, there was a steady stream of gas bubbles clearly visible through the acid pooled on the top. After the interruption, there were no bubbles and hence no gas flow at all despite exactly the same pressure setting. The explanation for this phenomenon is as follows: while gas is flowing through the hole, the acid is kept at the top surface and the inside walls of the pinhole remain dry. During the interruption, acid penetrates into the hole and wets the sidewall. When gas pressure is reapplied, it cannot push the acid back out of the hole due to surface tension. In essence, the pinhole has been sealed by the acid and no gas escapes. It was observed that the pinhole was slightly tapered to match the shape of the sharpened pin used to make the holes; therefore, acid entering the hole and moving lower will see a smaller diameter and hence larger surface tension forces, which makes it even more difficult for the gas to exhaust through the hole. This geometry is shown schematically in Fig. 9.

The pressure in a spherical gas bubble is governed by a simple equation:

$$\Delta P = 2T / r \quad [1]$$

where  $\Delta P$  is the pressure difference across the bubble wall,  $T$  is the surface tension and  $r$  is the radius of the bubble. The surface tension of 86% sulfuric acid at room temperature is 0.065 N/m.<sup>7</sup> In Test 2, the gas pressure was 5,000 Pa. If we model the gas-liquid interface in Test 2b as

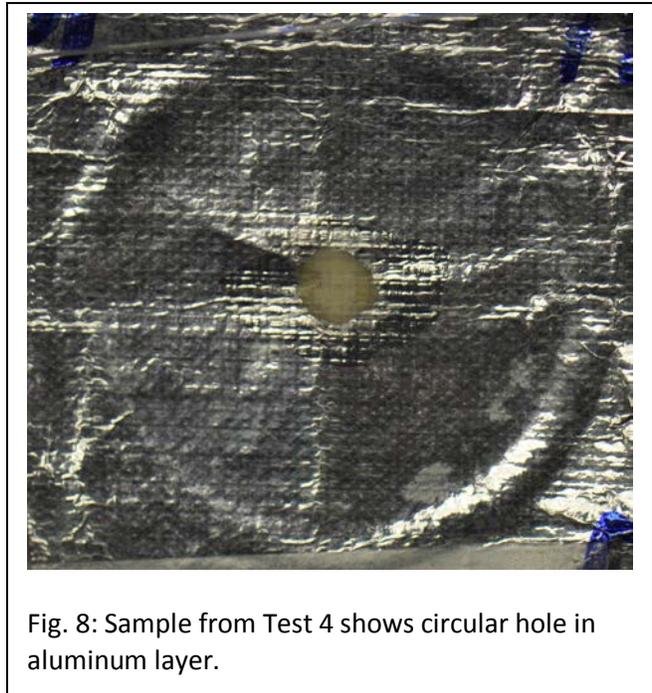


Fig. 8: Sample from Test 4 shows circular hole in aluminum layer.

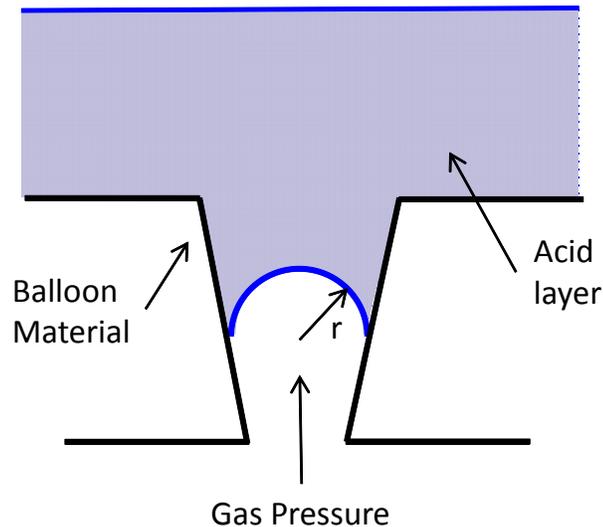


Fig. 9: Schematic diagram showing air bubble trapped in a pinhole.

a spherical bubble, we can use Eq. 1 to estimate the radius of the hole. Substituting values, we compute that:

$$r = 2T / \Delta P = 2 (0.065) / 5000 = 26 \mu\text{m} \quad [2]$$

For such a simple model, this value of 26  $\mu\text{m}$  radius compares favorably to the microscope measured Test 2 pinhole size at the top surface of 40  $\mu\text{m}$  radius (80  $\mu\text{m}$  diameter). The agreement becomes even better when the tapering of the hole is accounted for given that the interface was likely located in a narrower part of the hole.

This blockage phenomenon indicates that the two possible origins of a pinhole could have very different effects on the balloon lifetime. If the pinhole is created before acid wets the hole, then gas will leak out continuously until buoyancy is lost over the many day or week timescales depicted in Fig. 5. Conversely, one can imagine a scenario in which there is initial no through-hole but there is a scratch or other defect in the outer acid-resistant layers of the laminate. In this case, acid could react its way through the underlying aluminum and urethane layers and create a through-hole over time. If the resulting hole is sufficiently small, surface tension forces will be large enough to keep the acid from being dislodged by the gas, effectively plugging the hole. This second pinhole mechanism is very unlikely to shorten the mission below the one month threshold since no buoyancy gas will be lost and the damage rates listed in Tables 1 and 2 are too small to cause structural failures on this time scale, as will be argued below.

The data in Table 1 clearly shows that larger pinholes have higher growth rates of the damage area. Comparing Tests 3a and 4, for example, shows an order of magnitude increase in damage area growth rate (<0.1 to 0.8 mm/day) in going from an 80  $\mu\text{m}$  to a 210  $\mu\text{m}$  diameter hole. There is no evidence of a further jump in growth rate when the pinhole size was increased from 210 to 300  $\mu\text{m}$  in diameter in Test 5. The damage area growth rate for all pinhole sizes was seen to be essentially linear with time over the 1 to 13 day test durations that were measured. It is

important to note that the physical dimension of the pinhole itself does not change over time: the FEP or PFA layers are not harmed by the acid and therefore the ingestion area at the top of the hole remains constant. Nevertheless, the radial growth of the black spot does not change its rate despite the increase in perimeter over time and the fixed hole through which the acid can penetrate.

Test 7 shows that an increase in the acid concentration from 86% to 96% has a large effect on the damage area growth rate. The measured damage area growth rate goes from  $< 0.1$  mm/day (Test 3a) to 0.3 mm /day with gas pressurization and flow, and from 2 mm/day (Test 3b) to 10 mm/day in the absence of gas flow. No other changes were observed when doing the higher concentration tests: the growth rate remained linear and the visible evidence of growing black spots appeared to the same as for the 85% concentration tests.

Test 8 was the last one performed and its purpose was to compare the PFA-based laminate with the FEP-based laminate (Tests 3a and 3b) at the 80  $\mu\text{m}$  hole size. The results listed in Table 2 show that there was no measurable difference between the two laminates under these conditions. The switch from a single layer of 25  $\mu\text{m}$  thick FEP film to a bilaminate of two 12.7  $\mu\text{m}$  thick layers of PFA film did not result in any difference in damage area growth rate or the character of the visible black spot seen around the pinhole.

Collectively, these results indicate that it will be very unlikely that acid damage will lead to a balloon structural failure during one month balloon missions at Venus. Since the Vectran fabric itself is highly resistant to sulfuric acid (Refs. 2 and 3), a balloon structural failure can only occur at the gore-to-gore seams when the adhesive on the connecting load tapes gets dissolved. These load tapes are 50 mm in width and are located on the inside balloon surface. Therefore, a failure requires that acid enter the balloon and dissolve a sufficiently large amount of adhesive at a seam. Given the slow growth rates measured in these experiments, the pinhole would need to be located at or very near a seam to for a seam region to get exposed to acid at all. The 50 m tape width is an appropriate length scale for how far the acid damage would have to spread to cause a structural failure. Give the growth rates listed in Tables 1 and 2 for cases where gas is venting out through the pinhole, it would take 50+ days with 86% acid concentration and  $\sim 17$  days with 96% acid concentration to even create a black spot 50 mm in diameter around the pinhole. Whether or not this would also correspond to a sufficient loss of adhesive within this area to cause structural failure of the seam is uncertain: a significant amount of acid has to get inside to react with and weaken or destroy the aluminum, polyurethane and adhesive inside that circle.

Note also that acid must be at the location of the pinhole itself for there to be any problem whatsoever. As discussed above, there was little evidence with the VEGA balloons of any substantial acid accumulation on the total balloon envelope during those missions, let alone significant accumulation at any one particular location where there might be a pinhole. The balance of probabilities therefore suggests that the likely effect of a pinhole in the balloon envelope will be the loss of buoyancy gas that may curtail the mission below 30 days depending on the size of the hole, plus the formation of a little black spot over time if any acid aerosols happen to deposit and stick at the particular location. These black spots will experience elevated temperatures due to the absorption of sunlight, but there will be little effect on the overall buoyancy gas temperature and pressure given their very small size compared to the overall balloon surface area. For example, even if as much as 10% of the balloon envelope surface were to be covered in black spots with an effective solar absorptivity coefficient of 90%, the estimated

increase in balloon temperature is 18 K and balloon pressure is 3,000 Pa. Neither poses a serious threat to the thermal and structural safety margins in the design.

## Conclusions

This paper has described analyses and a series of experiments concerning the effect of pinholes in Venus balloon material recently developed by a partnership led by JPL. For a 7 m diameter spherical superpressure balloon, analysis shows that helium gas loss alone will curtail the planned mission below its 30 day design lifetime at Venus if there is a single pinhole greater than 190  $\mu\text{m}$  in diameter. Acid exposure tests on deliberately pinholed material samples indicate that very little damage occurs while gas escapes out through the hole. The damage manifests itself as a black circle around the hole due to oxidation of the metal and adhesive layers. If acid gets into the pinhole, then surface tension forces at these scales will block the gas from escaping. Acid-induced damage at the blocked pinholes occurs more quickly than in cases where gas is flowing. Larger pinholes and higher acid concentrations similarly cause damage to the material as a faster rate. However, all test results from deliberately pinholed material samples indicate that the acid damage occurs too slowly to cause a structural failure that would limit a Venus balloon mission to less than one month, even under worst case conditions that the pinhole gets wetted by significant amounts of acid at the start of the mission.

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