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# Current status of a super-pressure balloon research of new design concept

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***Abstract:*** A super-pressure balloon, which can reach the stratosphere with a heavy payload and continue to fly without ballasting, is quite useful for a long duration circum-polar flight. It has been quite difficult to develop such kind of balloons because of large pressure applied to the balloon film. The authors have investigated a new balloon design concept which reduces the film tension dramatically so as to enable the balloon to withstand high pressure. Experimental research has been proceeding to use the different size model balloons step by step. This report describes the current status of our research and development of the super-pressure balloon. The first successful flight test in the world for the balloon using this concept is also reported in this paper.

## 1. Introduction

In 1991 and 1993, PPB (Polar Patrol Balloon) campaign were performed at Syowa Station, Antarctica. Seven balloons were launched there and three of them accomplished perfect circumpolar flights (Ejiri *et al.*, 1993; Nishimura *et al.*, 1994). The most long flight duration was 26 days. In that case the ballast occupied almost 40% of the initial payload weight of 250 kg, although the ballast consumption at the polar region was relatively less than that of at middle latitude in the summer season. Therefore, some scientists asked us an applicability of a super-pressure balloon which need not drop ballast to keep a constant altitude. A lot of payload weight can be allotted for scientific instruments if the balloon could be prepared without substantial increase of its weight. Unfortunately, at that time, we had not a large super-pressure balloon which could substitute for a conventional large zero-pressure balloon.

To realize a large super-pressure balloon, which can reach the stratosphere with a heavier payload, is an important research subject of the modern scientific ballooning for the latter half of this century. Major efforts have been made to develop stronger balloon film based on the latest high technologies of material science. In those cases the balloon design have based on a conventional concept. Such kinds of efforts, however, have not made enough progress.

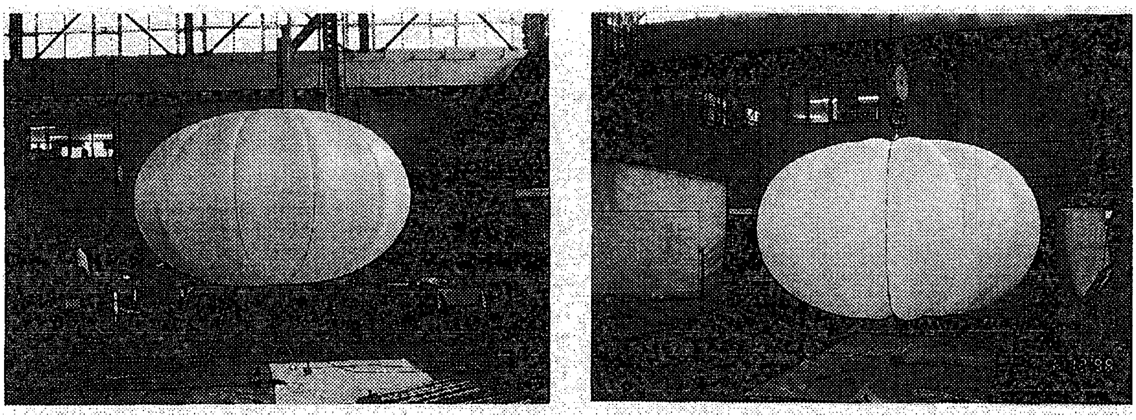
The authors have investigated this research subject from another point of view. Our approach is to obtain an extra strength balloon through a new balloon design concept, named 3-D gore design (Yajima, 2000; Yajima *et al.*, 1999). According to this new design method, a gore forms a large bulge with a small circumferential radius, $R_c$, between adjacent load tapes without any help of film elongation. Such a gore shape is obtained by adding excessive film along not only the circumference but also the meridian and by fixing the side line of the gore to the shorter load tape by a controlled shortening ratio. Then, the meridional tension, $T_m$, becomes zero and only the circumferential tension, $T_c$, appears on the film under the differential pressure $P$ according to the membrane theory. Then $T_c$ is simply derived as the product of $P$ and $R_c$. The tension $T_c$ becomes extremely small in proportion to the small local circumferential radius $R_c$. In addition, this bulge radius $R_c$ does not depend on the balloon volume, because the bulge width between the adjacent load tapes is defined by the original film width. This relation means an important fact that the balloon strength does not depend on its volume. The large super-pressure balloon can be realized owing to this unique characteristic.

The external form of this balloon looks quite different from an ordinal zero-pressure balloon. It forms flattened shape, so-called pumpkin, because its volume approaches to be maximum under the constraint of meridional length limited by low extensible load tapes.

## 2. A series of super-pressure balloon models

Experimental research has been proceeding to use the different size model balloons. As the first step, a small handmade model of 1 m in an equatorial diameter was manufactured in January 1998 to confirm the possibility of a large bulge formed by 3-D gore design. The second model was a balloon of 3 m in diameter. The gore material was a thin nylon fabric with urethane coating as a gas barrier. The ultimate strength of the fabric was 10 kN/m at 30% elongation. The load tape was a Kevlar rope of 3500 LBS (16000 N) in strength; twelve load tapes were used. The gores were joined like a parachute using a sewing machine and the seams were covered with hot melt seal tapes. The designed bulge radius was 0.5 m. Then the theoretical burst was 200 hPa. The third model of 100 $m^3$ in volume was manufactured for the verification of a new fabrication method that manages to fit the longer gore to the shorter load tape with wrinkles using a computer controlled sewing machine. In this case the ultimate strength of the fabric was 7 kN/m. The bulge radius was designed to be 0.8 m so that the maximum gore width was coincident with the effective film width of 1.35 m. Then the theoretical burst pressure was 88 hPa. The strength of the load tape was 4000 LBS (18000 N) and the number of load tapes was 18. Based on the successful test results of previous balloons, the first flight model balloon of 3000 $m^3$ volume with 55 load tapes was manufactured in March 1999 as a scale-up version of the 100 $m^3$ balloon.

The burst test of the 3 m balloon was carried out in June 1998. The balloon withstood till 187 hPa which was 3.4 times stronger than the same size balloon designed by the conventional manner (Akiba *et al.*, 1991). Figure 1 shows the external appearance of two types of the same size balloon under low pressurization. The balloon on the left was conventional and the right 3-D gore design. It is clear that the bulge shape of the conventional design balloon (left) is flat, but the 3-D gore design balloon (right) has lobed shape at this stage. The burst pressure also exceeded the similar size sphere balloon which was tested as the first phase of NASA's ULDB program (Smith *et al.*, 1998). An indoor full-inflation test of a 100 $m^3$ balloon was performed in February 1999. The 3-D gore shape achieved by the "gathering" sewing process was satisfactory as shown in Fig. 2. Though the balloon was not pressurized over 50 hPa for safety reasons, it appeared to have enough strength in reserve. Prior to the actual flight, the 3000 $m^3$ balloon was also



(a) Conventional design (b) 3-D gore design

*Fig. 1. Comparison of the shapes of 3 m balloons of conventional design (a) and 3-D gore design (b).*

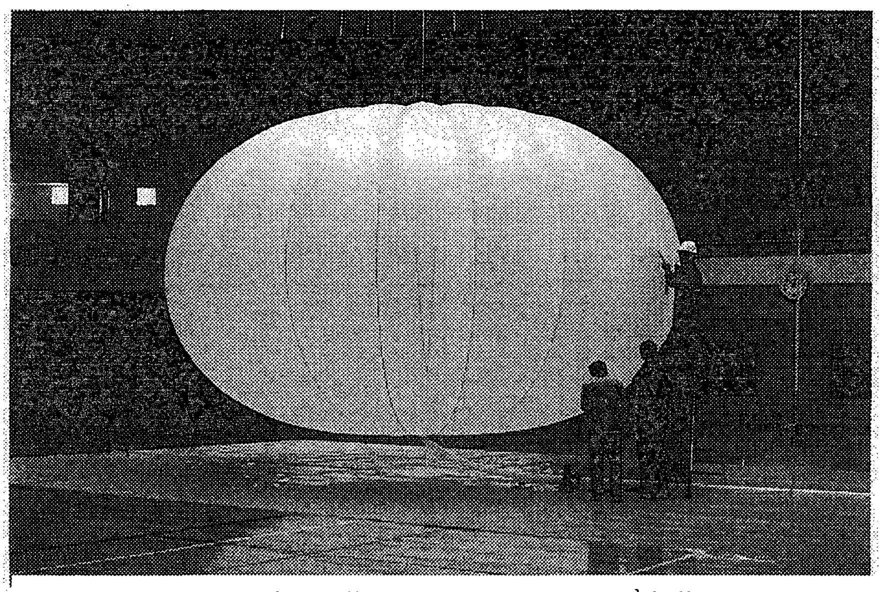


*Fig. 2. Indoor full inflation test of the100 m³ balloon.*

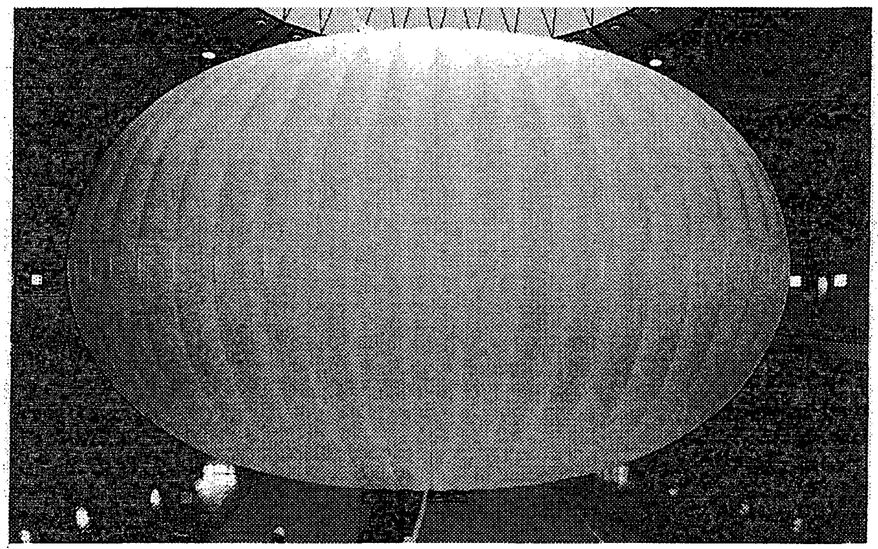


*Fig. 3. Indoor full inflation test of the 3000 m³ balloon.*

*Table 1. List of the test balloons*

| Model No. | #1 | #2 | #3 | #4 | #4' |
|---|---|---|---|---|---|
| Volume (Diameter) | (1 m) | (3 m) | 100 $m^3$ | 3000 $m^3$ | 3000 $m^3$ |
| Film strength | — | 10 kN/m | 7 kN/m | 7 kN/m | 7 kN/m |
| Elongation | — | 30% | 30% | 30% | 30% |
| Bulge radius | — | 0.5 m | 0.8 m | 0.8 m | 0.8 m |
| Number of load tapes | 8 | 12 | 18 | 55 | 55 |
| Load tape stiffness | — | 3500 LBS | 3500 LBS | 4000 LBS | 4000 LBS |
| Designed max. pressure | — | 200 hPa | 88 hPa | 88 hPa | 88 hPa |
| Max. test pressure | — | 187 hPa*1) | 50 hPa | 10 hPa*2) | 15 hPa |
| Date | Jan. '98 | June '98 | Feb. '99 | March '99 | May '99 |

*1) Actual burst pressure.
*2) Suspended due to the top part failure.

tested indoors twice in March and April 1999. The balloon was fully inflated and its pressurized behavior was carefully observed as shown in Fig. 3. In the first test, there was a short split in the film near the apex when pressure reached 10 hPa, due to the lack of the circumferential fullness. For the second test, the balloon was pressurized to 15 hPa successfully and also appeared to have enough strength in reserve. A list of test balloons and their specifications mentioned above is presented in Table 1.

## 3. Flight test

The flight test of the balloon of 3000 $m^3$ in volume was performed in May 1999 at Sanriku Balloon Center, Japan. The parameters of this flight test are listed in Table 2 and the profiles of the balloon altitude and pressure are shown in Fig. 4. The balloon stopped ascending at the altitude of 19 km under the pressure difference of 13 hPa. In this pressure, 6.5 hPa is derived from the product of the free lift rate (10%) and the ambient pressure (65 hPa). The remained pressure of 6.5 hPa is due to the heat-up effect caused by the solar radiation. By the meteorological data, the ambient temperature at the altitude of 19 km was 216 K. Therefore, the pressure of 6.5 hPa corresponds to the fact that the temperature of the buoyant gas is 18 K higher than that of the ambient atmosphere.

*Table 2. Parameters of the flight test.*

| | |
|---|---|
| Balloon volume | 3000 $m^3$ |
| Balloon weight | 151 kg |
| Payload weight | 36 kg |
| Ballast weight | 90 kg |
| Rigging weight | 11 kg |
| Total weight | 288 kg |
| Free lift | 35 kg |

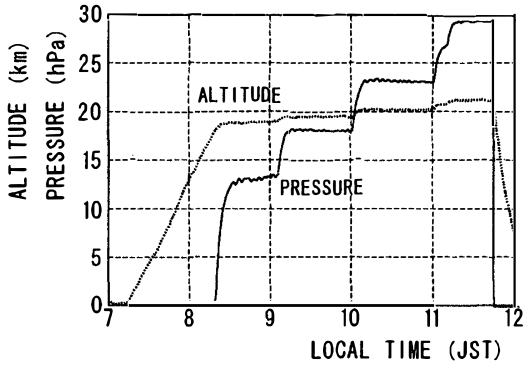



*Fig. 4. Profiles of altitude and pressure during the flight test.*

Then we dropped the ballast intermittently and pressurized the balloon more and more in order to verify the balloon strength. When all of the ballast of 90 kg was consumed, the balloon reached the altitude of 22 km and the pressure difference increased to 29 hPa which was 64% of the ambient pressure (46 hPa). At this moment the total meridional tension supported by 55 load tapes was about 1000 kN. The tension

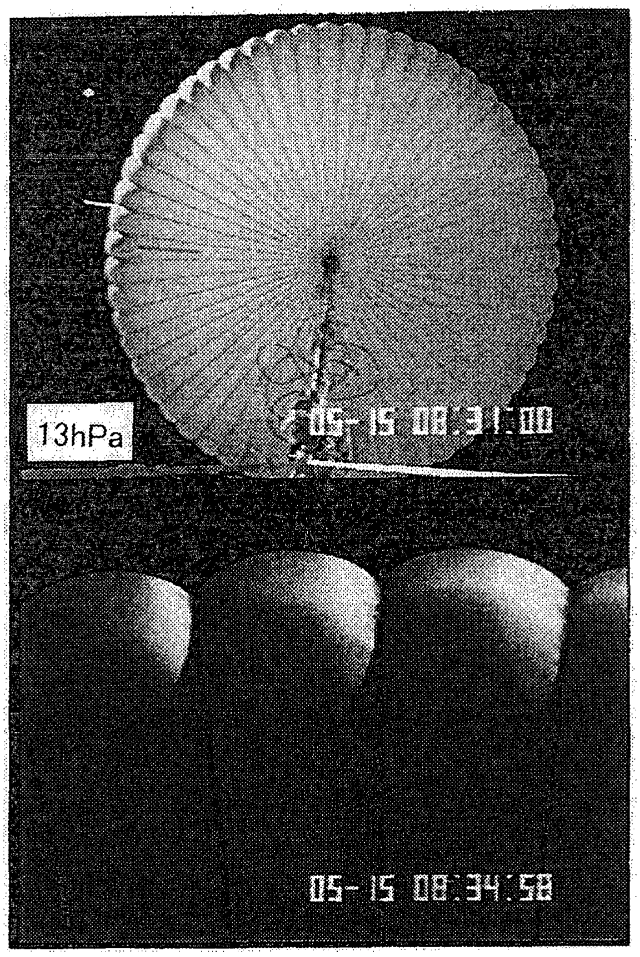



*Fig. 5. Outside view of the balloon looked up from the on-board camera.*

of 18 kN was applied to one load tape and this value exceeded the ultimate strength of 4000 lb (17.8 kN) Kevlar rope. The flight was terminated 30 min after due to the break of the load tape.

Figure 5 shows the shape of the balloon looked up from an on board camera attached on the payload. In this picture we can see the film formed large bulges between load tapes. Since the straight distance between the adjacent load tapes is known, the bulge radius of 0.8 m is estimated from this picture. This radius is almost the same as the designed value.

## 4. Conclusion

A unique super-pressure balloon has been developed by applying our new balloon design concept. The flight test demonstrated the extra strong characteristic of this new balloon. This result is the first epoch-making record in the world. It will be possible to construct a large super- pressure balloon which can reach more than 30 km with a heavy payload will be achieved by this concept. The authors believe that this type of super-pressure balloon will play a leading role of a long duration balloon experiment including the observation at the polar region in the next century.

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