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# Ballast saving balloons with a film of specific optical properties

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***Abstract:*** Large plastic balloon play an important role for scientific observations at high altitude in the field of astrophysics and geophysics. In these observations, it has been well recognized that the long duration balloon flights are indispensable for precise observations. For a normal zero pressure balloon, we need to drop ballast to keep a level altitude during day and night to prevent from altitude excursions. This is due to the temperature change of lifting gas, and the duration of the balloon is limited when all the ballast on board the balloon has been exhausted. In this paper, we discuss a possibility of minimizing the temperature variation of the lifting gas using specific balloon films with suitable optical properties and show the optical properties of some test films for this purpose.

## 1. Introduction

In balloon observations, long duration flights have been an important technical challenge to perform precise scientific observations, and much efforts has been expended. As is well known, the basic problem for the long duration flights is the temperature change of the lifting gas during the day and night excursions. In the case of zero pressure balloons, the temperature of lifting gas decreases after the sunset and the lift of the balloon decreases. The floating balloon starts to descend, and we need to drop ballast to keep the balloon at a level altitude. For a polyethylene balloon, the ballast consumption each day is about 10% of the net weight of the balloons for mid-latitude flights. Thus the duration of the flight is limited when all of the ballast on board the balloon is exhausted. The flight duration is at most several days for mid-latitude flights. This thermal condition is much relaxed in the summer season in the polar regions where there are almost no sunset. Such balloon flights have been performed from Syowa Station and McMurdo Station in Antarctica. Balloon observations at level altitude have been successfully achieved for 10 to 20 days (Nishimura *et al.*, 1994; Ejiri *et al.*, 1994; Jones, 1994). Recently, a program in the Arctic region had also been performed by US balloon group from Fairbanks, Alaska with the flight durations up to about 10 days (Jones, 1999).

The super pressure balloon is the most orthodox one flowing at a constant altitude without consuming ballast. Up to now, super pressure balloons were successfully constructed for only small balloons with volume of several thousand m$^3$ with light weight payloads, because of the technical difficulties in fabricating balloons with strong film for the super pressure. NASA is planning a new program for reasonable size balloon (several hundred thousands $m^3$) with a payload of about 1600 kg for the flight duration of 100 days in 2001 (ULDB Web page; Smith, 1999; Said, 1999; Yajima *et al.*, 1999; Shur *et al.*, 1999). To realize this program, some technical improvements and studies are now under investigation to develop strong films and reasonable structures for these balloons (Smith and Schallenkamp, 1996; Yajima *et al.*, 1999).

In this paper we investigate another possibility to reduce the ballast consumption, by reducing the temperature change during day and night flights. The temperature of lifting gas at high altitude is dependent on mainly the radiation process, that is on the ratio of absorption coefficient of optical ($\alpha$) to infrared ($\varepsilon$). If we have a balloon with the ratio '$\alpha/\varepsilon$' smaller than that of polyethylene balloon film, its temperature increase during the daytime could be smaller. Meanwhile, the gas temperature at night is almost independ of this ratio, as shown later. Thus, for a balloon with suitable optical properties, the difference in temperature during the day and night is reduced compared with that of a polyethylene balloon, and we can reduce the ballast consumption. Such a concept had already been discussed in 1970's by mixing some gaseous material with strong infrared absorption to the lifting gas. However, it was difficult to find a suitable material and the idea has not been realized.

It is also possible to achieve the desired optical properties by using balloon films with smaller '$\alpha/\varepsilon$' compared with that of the polyethylene. In fact it has been proposed that EVAL (films of Ethylene-Vinyl-ALcohol) film is one of such candidate. The test flights of the EVAL balloon have been conducted and now continue (Nishimura, 1996; Saito *et al.*, 1999). If we use films other than polyethylene, we need to pay attention to the mechanical properties of those films. As is well known, balloon films must have good mechanical properties at low temperature for successful flights in high altitude. The polyethylene film has a long history of development for balloon use, and now, is used as the most reliable material. Thus it is desirable to use the polyethylene film as a basic material for a balloon.

Here we propose to use the polyethylene film as the base, and coat or mold other materials with suitable optical properties. In Section 2, we first review the thermal conditions of balloons at high altitude. Then we illustrate that the temperature difference of the lifting gas inside the balloon during day time and night time is mainly determined by the ratio, $\alpha/\varepsilon$, of optical absorption coefficient, $\alpha$, and of infrared, $\varepsilon$. In Section 3, we search for possible materials to be printed on or molded in the balloon films, and find that $BaSO_4$ and a few other substances seem to be suitable for this purpose. We prepared test films with these materials, and measured the optical properties, while the test has not yet completed. Here, we report the optical properties of the test films, and the future prospects of these films for balloon use.

## 2. Thermal analysis of a balloon at high altitude

We summarize briefly the theoretical aspect how the temperature of the lifting gas depends on the optical properties of balloon material (Nishimura *et al.*, 1973; Cathey, 1996). The energy balance of a balloon floating at a level altitude is shown in Fig. 1. As shown in this figure, heat transfer of the balloon films arise from

- the absorption of solar radiation and its albedo from the earth,
- the absorption of infrared radiation at the level altitude from the earth,
- the emission of infrared radiation from the balloon films,
- the convection of the heat with outer atmosphere and the lifting gas.

The spectra of the solar radiation and infrared radiation from the surface of the earth at the balloon altitude are shown in Fig 2.

Notation used in this paper is summarized in Table 1. $\varepsilon$ and $\varepsilon'$ could be slightly different, since the incoming infrared from the earth has a specific spectral shape due to the absorption of the atmosphere as shown in Fig. 2.

As in many cases for the thermal analysis of a floating balloon, we assume the temperature of lifting gas is the same as that of balloon film. Under this assumption, we obtain an average value of gas temperature, since the lifting gas, He or $H_2$, does not have any significant absorption bands in the optical to infrared region where we are concerned.

It is also known that the temperature of balloon film is mainly determined by the

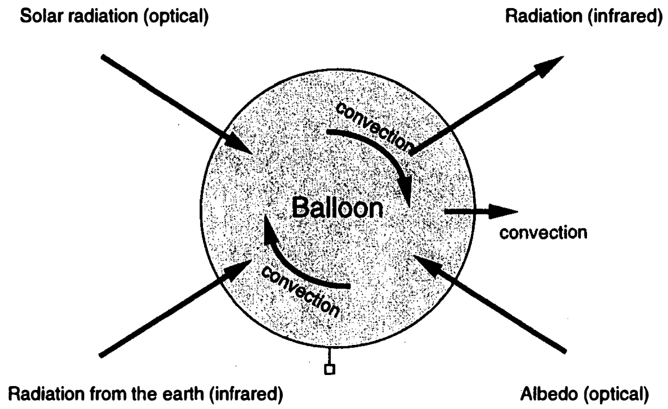


*Fig. 1. Balloon energy balance.*

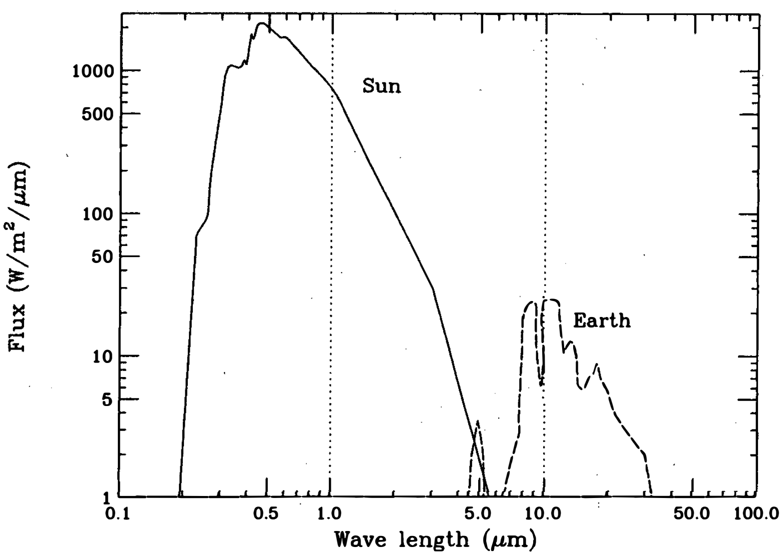


*Fig. 2. Spectrum of the solar radiation and infrared radiation from the surface of the earth at the balloon altitude.*

*Table 1. Notation.*

| | | |
|---|---|---|
| $\alpha$ | : | Effective optical absorption coefficient of the balloon film. |
| $\varepsilon'$ | : | Effective infrared emission coefficient of balloon film. |
| $\varepsilon$ | : | Effective infrared absorption coefficient of the balloon film. |
| $\sigma$ | : | Stefan-Boltzmann constant ($\sim 5.67\times10^{-8}$ W/m$^2$K$^4$) |
| $T$ | : | Temperature of the balloon film. |
| $J_0$ | : | Solar radiation ($\sim 1.3\times10^3$ W/m$^2$) |
| $J_0'$ | : | Albedo of the Solar radiation from the earth. It changes with the surface condition of the earth. The average value is about 0.3 $J_0$. |
| $J_1$ | : | Infrared radiation from the earth observed at the balloon altitude. It changes with the condition of the earth surface, and the average value ranges between 250~300 m W/m$^2$ at mid-latitude. |

radiation effect at high altitude. The effect of heat convection in the atmosphere does not play a major role for the temperature change (Nishimura *et al.*, 1993; Cathey, 1996).

Approximating the balloon shape by a sphere with a radius of $R$, the equilibrium of the energy balance for the balloons floating at a level altitude is given by the formula:

$$4\pi R^2\sigma\varepsilon' T^4 = \pi R^2 (\alpha (J_0 + J_0') + 2\varepsilon J_1). \tag{1}$$

During night time, $J_0 = J_0' = 0$, and we have the night temperature $T_n$ determined by the radiation from

$$2\sigma\varepsilon' T_n^4 = \varepsilon J_1. \tag{2}$$

If $\varepsilon' = \varepsilon$, the night time temperature is always the same without depending on the optical properties of the balloon material.

Next, we find the day time temperature $T_d$ in the following formula as:

$$4\sigma\varepsilon' T_d^4 = (\sigma (J_0 + J_0') + 4\sigma\varepsilon' T_n^4), \tag{3}$$

and

$$\frac{T_d}{T_n} = \left(\frac{\alpha(J_0 + J_0')}{4\sigma\varepsilon' T_n^4} + 1\right)^{\frac{1}{4}} = \left(\frac{\alpha}{\varepsilon}\cdot\frac{(J_0 + J_0')}{2J_1} + 1\right)^{\frac{1}{4}}. \tag{4}$$

It is to be noted that the ratio of the daytime and nighttime gas temperatures is proportional to the ballast consumption and is dependnet on the ratio $\alpha/\varepsilon$. This result is naturally understood as follows. If the material does not absorb the solar radiation (small $\alpha$), or, shows heavy absorption of the radiation from the earth (large $\varepsilon$), the energy input is independent of time and the temperature will be constant.

## 3. Selection of materials with small $\alpha/\varepsilon$

In the preceding section, we showed that the ballast consumption is directly related to the value of $\alpha/\varepsilon$ of the balloon film. A smaller value of $\alpha/\varepsilon$ is preferable to reduce the ballast consumption. We found a table for some coating materials for the thermal control of the satellites in a handbook (Gilmore and Bell, 1998).

The candidates with small $\alpha/\varepsilon$, are shown in Table 2, in which we also put the values of other plastic balloon films for comparison.

In this table, we need to take into account that the $\alpha/\varepsilon$ values listed are for cases when it was coated on the surface in rather thick layers. Thus the values may not be the same in the case of films with thin coating or molding of these materials. In any case, the values listed in the table give us a guide line to select the materials to be coated or molding on the balloon films.

Aluminum coating seems to be preferable since it reflects the solar radiation efficiently. However, it has less absorption in the infrared region. It is expected that the lifting gas heats up during the daytime more than that of a polyethylene balloon and in this case the aluminum coating should be discarded.

Aluminium coating was successfully used by French group to realize the Mongolfiere Infra rouge (Pommereau and Hauchecorne, 1978; Lettrenne *et al.*, 1999). They are essentially hot air balloons using aluminium coating inside the films at the upper half of the balloons to keep the gas temperature high. They succeeded in floating the balloons for a few months, while it was difficult to get high altitude more than 30km because of their smaller lift than He balloons.

$TiO_2$ and ZnO are generally used as a coating material of a good reflector. However, they may not be suitable for our purpose, since $\alpha/\varepsilon$ ranges of these are almost the same values of polyethylene film.

*Table 2. Optical properties of various materials.*

| Plastic films | | | | |
|---|---|---|---|---|
| Material | $\alpha$(Solar) | $\varepsilon$ (IR) | $\alpha/\varepsilon$ | Reference |
| Polyethylene | 0.023 | 0.077 | 1/3 | Cathey, 1996 |
| Mylar | 0.1 | 0.6 | 1/6 | Nishimura, 1996 |
| EVAL | 0.1 | 0.9 | 1/9 | Nishimura, 1996 |
| Coating material (from NASA Technical Report, 1983) | | | | |
| Material | $\alpha$(Solar) | $\varepsilon$ (IR) | $\alpha/\varepsilon$ | |
| Al | 0.08 | 0.04 | 2 | |
| $TiO_2$ | 0.20 | 0.90 | 1/4.5 | |
| ZnO | 0.15 | 0.92 | 1/6 | |
| Ag | 0.09 | 0.88 | 1/10 | |
| MgO | 0.09 | 0.90 | 1/10 | |
| $BaSO_4$ | 0.06 | 0.88 | 1/15 | |

We can select MgO and $BaSO_4$ from the Table 2 as practical and possible candidates. If we take the values of these materials in Table 2, we could expect almost 1/3~1/4 of the temperature change from formula 4 during day and night excursion as compared with the case of a polyethylene balloon. This means we can expect to reduce the ballast consumption by 1/3~1/4.

It is also important to compare the additional weight of the painted or mixed material to the reduced ballast. Typically, the total weight of a balloon system including a payload is twice the weight of the balloon itself. Thus, the ballast consumption per night is about 20% of the balloon weight. If it is possible to use a film with the suitable optical properties adding the material within 20% of the balloon weight, we can reduce the initial weight of the balloon systems for more than a few days flights. This limitation looks feasible referring to data of test films as shown in the next section.

## 4. Optical properties of test films

As mentioned in the preceding section, the value $\alpha/\varepsilon$ for the coating material is based on the case of a thick enough coating. Thus we need to measure the optical properties for thin coating or molding of these materials. We report here some results of the measurements in the infrared band.

We prepared the following three types of films to see the performance of these films containing materials with the excess weight less than 10%. The excess weight of these films meet the weight requirement for ballast saving in Section 3.

- $BaSO_4$ mold films: 10% in weight of $BaSO_4$ with grain size of 0.7 $\mu$m was molded in a polyethylene film with a thickness of 20 $\mu$m.
- $TiO_2$ mold film: 5% in weight of $TiO_2$ was molded in a polyethylene film of thickness of 40 $\mu$m. The amount of $TiO_2$ in this film is equivalent to 10% excess in weight for a 20 $\mu$m polyethylene film. This film is commercially available (Dai Nippon Printing Co. Ltd.). The grain size of $TiO_2$ is ~1 $\mu$m.
- $TiO_2$ mold film attached by carbon molded film, each of thickness of 12 $\mu$m: 9% in weight of $TiO_2$ and 6.4% of Carbon powder was molded in each film. This film is also commercially available, and adopted to measure the optical properties for the comparison. The grain sizes of $TiO_2$ and carbon are both ~1 $\mu$m.

We measured the optical properties from 2.5 $\mu$m to 20 $\mu$m, almost covering the infrared radiation at the balloon altitude. The measurement is performed by a Fourier transform spectrometer (FTS-60A/896, Bio-Rad Laboratories Inc.).

Figures 3, 4 and 5 show the results of the measurements. Wavy structures are due to the interference of the lights due to the thickness of the films being comparable to the measured wavelengths. We see the polyethylene absorption bands around 3.3, 6.9, 13.8 $\mu$m in these figures.

Heavy absorption was found around 7 to 10 $\mu$m and 16 $\mu$m for $BaSO_4$ mold film, and above 12 $\mu$m for $TiO_2$ mold film. We also measured absorption properties of a $BaSO_4$ painted film and obtained similar properties. In the wave region of 7 $\mu$m to 14 $\mu$m where the flux of infrared from the earth is dominated, a significant absorption was observed in $BaSO_4$ molded films over the $TiO_2$ molded films. Comparing the results shown in Figs. 4 and 5, the carbon molded film indicates continuous absorption without

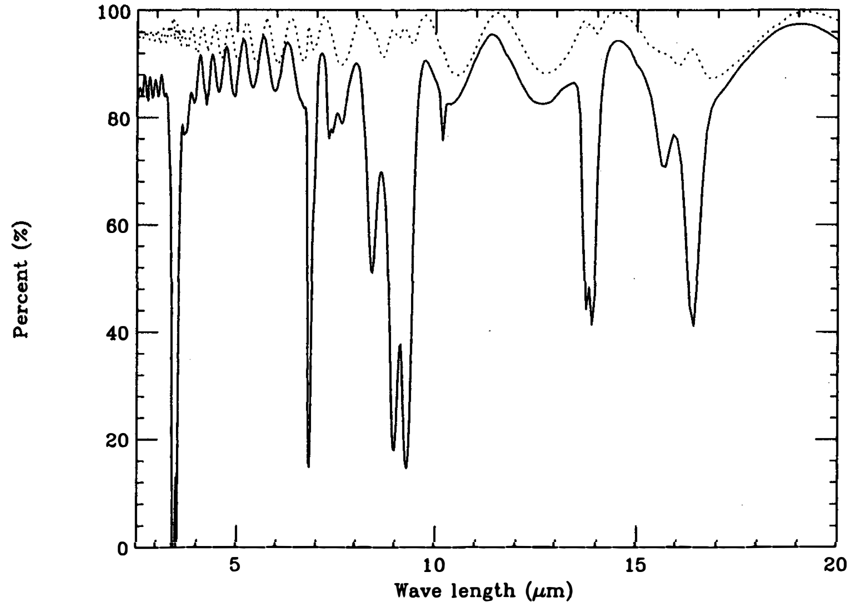


*Fig. 3. Optical properties of $BaSO_4$ mold film. Solid line indicates the transmission and dotted line the reflection.*

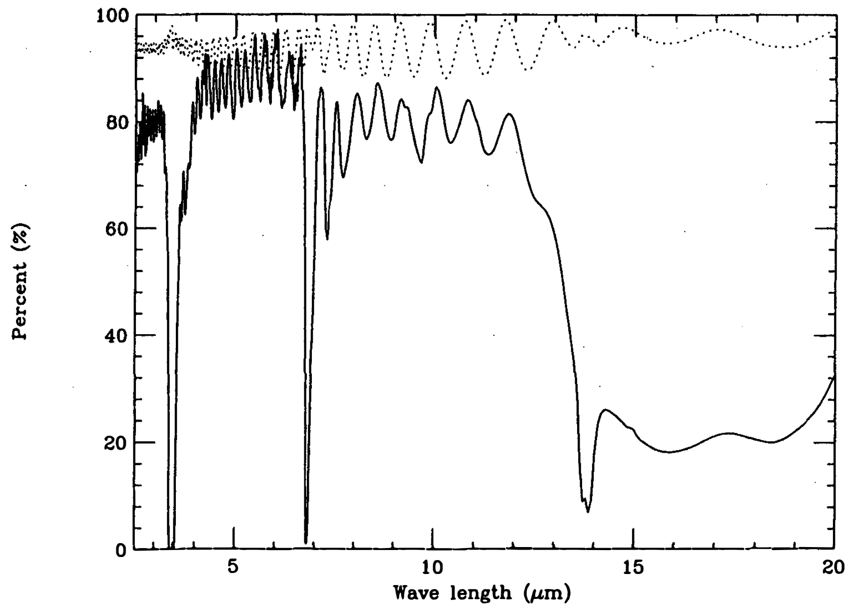


*Fig. 4. Optical properties of $TiO_2$ mold film. Solid line indicates the transmission and dotted line the reflection.*

any particular strong absorption band.

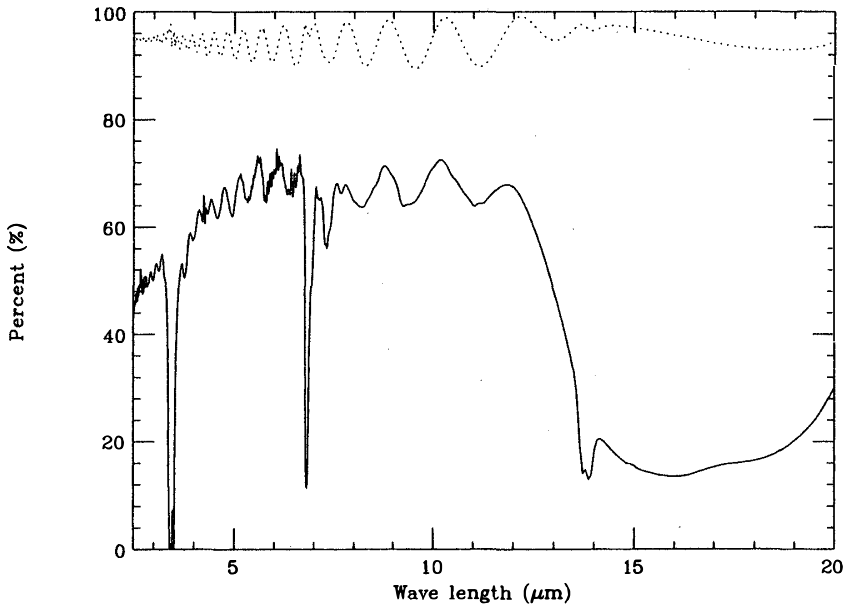


*Fig. 5. Optical properties of $TiO_2$ mold film attached by a carbon mold film. Solid line indicates the transmission and dotted line the reflection.*

## 5. Summary

In order to achieve a long duration balloon flight, we investigated the possibility to reduce the ballast consumption by using balloon films of suitable optical properties. The films must have the properties of smaller $\alpha/\varepsilon$ than that of polyethylene balloon films. We may expect a smaller temperature change with films of smaller $\alpha/\varepsilon$ during day and night excursion, and thus the ballast consumption is expected to be reduced as compared with that of a polyethylene balloon.

The idea here proposed is to use polyethylene films but coated or molding with a small amount of a material with a small $\alpha/\varepsilon$. The material is usually used for the surface of satellites to avoid the temperature increase by the solar radiation. Among these, $BaSO_4$ and MgO seem to be suitable for our purpose. The ballast consumption could be reduced by a few times if it works as we expect, and will give us a great benefit for the long duration flights.

We prepared three test films containing $BaSO_4$, $TiO_2$ and Carbon powder, and measured their optical properties as shown in Figs. 3, 4, and 5. We have completed the measurements in the infrared band from 2.5 to 20 $\mu$m. Certain absorption has been observed in these films, and seems to be satisfactory. Among these, films containing $BaSO_4$ seems to be the most promising as we had expected. The excess weight of this film is only about 10% and it is expected to reduce the total weight of a balloon system by saving the ballast weight in spite of slight increase of the weight of the balloon film, as discussed in Section 3. Since small absorption properties in the optical band are also required, we are going to measure the properties of these films.

We are now preparing new test films with a different material (such as MgO and others) as well as with a different mixing ratio in the films, to find the most suitable films for this purpose.

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