THE DESIGN AND USE OF PLASTIC BALLOONS FOR STRATOSPHERIC RESEARCH IN INDIA

by

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ABSTRACT

Plastic balloon flying has been developed at the Tata Institute of Fundamental Research as a research technique which has a number of important applications in India: (*a*) cosmic ray studies; (*b*) air sampling in the stratosphere for fall-out measurements; (*c*) meteorological investigations; (*d*) astronomical observations; (*e*) defence research. Comparatively little work has been done till now in these fields at equatorial latitudes, particularly at stratospheric altitudes.

Large plastic balloons with volumes of the order of half a million cubic feet, and more, have been constructed by heat welding polyethylene sheeting 0·0015″ thick. With these balloons, successful level flights at altitudes of 110,000 ft. have been achieved; in some cases, individual loads weighing a hundred pounds have been carried up.

The most serious problem encountered is the extremely low temperature, (about —85°C), of the tropopause at the equatorial latitudes; all known plastics for balloon manufacture become brittle at these low temperatures. To overcome this, dark fabrics have been employed so that the material is heated by solar radiation. The plastic sheeting employed is extruded in India to balloon specifications from chosen polymers.

The low temperatures and the turbulent conditions that prevail in the atmosphere at low latitudes present problems in balloon flying which are different from those encountered at high latitudes. The techniques employed, the design of the balloons, and their performance under these conditions are discussed.

Introduction

With plastic balloons it is possible to carry equipment to predetermined levels of the atmosphere and to hold it there for observations over extended periods of time. The advantages of plastic balloons over rubber balloons for level flights of long duration, and for carrying heavy loads, are too obvious to need enumerating. Already, with plastic balloons, level flights ranging from a few hours to several days, at altitudes upto 140,000 ft. and in some cases carrying loads of the order of a ton or more, have been achieved, mainly in the U.S.A.

In view of these features, a couple of years ago we initiated the Plastic Balloon Project at the Tata Institute of Fundamental Research in Bombay, to construct and fly large plastic balloons for stratospheric research in India. The primary objective was to carry electronic equipment and photographic emulsion stacks to high altitudes for research on cosmic radiation. It is clear, however, that this technique can be utilised in a variety of fields of research in India. The obvious fields of utilization are: (*a*) cosmic ray physics—particularly research on the primary component and its time variations; (*b*) meteorology—to study winds, temperatures, meteoric dust and ozone content at high altitudes; (*c*) to measure the radioactive content of the atmosphere at different levels, particularly fall-out arising from bomb explosions; (*d*) astronomy—to study astronomical objects unobstructed by the atmosphere; (*e*) defence science—to obtain information valuable for high flying jet aircraft and many other uses e.g., in the United States, rockets have been carried up on balloons and fired at high altitudes, thus eliminating their journey through the dense lower atmosphere, and nuclear weapons have been exploded from flying balloons. In each of these fields only a few of the uses have been mentioned as examples. There are also many other experiments which one can visualize using plastic balloons: for example, one could investigate the firing of shaped charges at high altitudes which would simulate meteor trails.

Plastic balloons have now been flown for nearly over a decade. They were first used on an extensive scale in the United States soon after the war; a few years later, the emulsion group of the Bristol University in England developed this technique independently for cosmic ray research. Mention may also be made of some work done by P. Demers in Canada. Flights of rather limited performance have been carried out sporadically by other groups. Most of these flights by European and American groups (and also in Japan), have been at high latitudes. The flights in Europe have also been, almost exclusively, for cosmic ray experiments. A few flights, with much more limited success, have been carried out by the American groups at equatorial latitudes. In view of the comparatively little work done at low latitudes using plastic balloons, it is clear that there is considerable scope for extensive and systematic studies involving use of this technique in India.

There are a number of novel features and difficulties encountered in flying plastic balloons at low latitudes; in particular, one has to deal with the extremely low temperatures and the highly turbulent conditions which prevail in the tropopause over these regions. We have overcome many of these problems and gained a certain amount of useful experience in these two years. In the rest of this is given an account of the techniques which we now employ and the reasons for adopting them.

The design and construction of plastic balloons

General Considerations: Plastic balloons are of the constant volume type; the material, which is essentially non-extensible, encloses a volume V when the balloon is fully inflated. The balloon will float at an altitude of x atmospheres where the following condition* holds:

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*It is assumed in the above that the volume, (V_c.) occupied by the hydrogen at ceiling altitude is equal to V, the fully inflated volume of the balloon. This need not be so if the excess pressure of hydrogen inside the balloon is insufficient to keep the fabric taut, particularly in the lower regions and when a heavy load is suspended. In such cases, V in the above formula should be replaced by V_c. One of the considerations governing balloon design is to make V_c= V i.e. obtain a full utilization of the volume of the balloon.

$$(W + L)/V = d\,(\text{air}; T_a, x) - d\,(\text{hydrogen}; T_h, x) \qquad (1)$$

where W = weight of the balloon

L = load carried up

$d\,(\text{air}; T_a, x)$ = density of air, at x atmospheres, at its temperature T_a

$d\,(\text{hydrogen}; T_h, x)$ = density of hydrogen, at x atmospheres, at its temperature T_h,

The balloons may be filled with any light gas. Helium has been employed in the U.S.A., where it is available cheaply. The balloons here are filled with hydrogen and, accordingly, all reference in this work will be to it.

The hydrogen which occupies a volume V at the ceiling altitude of x atmospheres will occupy a volume xV at ground level; thus, for a balloon which floats at about 10 mb., only 1 per cent of its volume is occupied by the hydrogen whilst it is at ground. As the balloon ascends, the small bubble of hydrogen at the top expands till it occupies the full volume V at ceiling. A balloon, if given only this quantity of gas, i.e xV will float at any altitude in the atmosphere (from ground level upto its ceiling), wherever it be placed; in making this statement, effects due to temperature are neglected. In order to make the balloon ascend, an extra amount of gas, referred to as free lift, f, is given to it. When the balloon reaches ceiling, the extra gas is expelled through an escape tube.

From considerations of fluid dynamics it can be shown that the rate of ascent, R, in ft/min., of a balloon is related to the free lift, f, and, gross lift, G (= W + L + f), both in kgms, by the following equation:

$$R = K\,x\,\sqrt[2]{f}\,/\,\sqrt[3]{G} \qquad (2)$$

where K is a constant (given essentially by the Reynolds number).

For rubber balloons K has a value around 1600. The determination of K for the plastic balloons flown here is described later on in this paper (Section III).

Construction: The balloons are made from polyethylene film ·0015″ thick, which is available in the form of sheeting several hundred yards long and a few feet wide. The sheets are cut into lengths corresponding to the deflated length of the balloon (of the order of 150 feet), and laid one on top of the other on long tables. They are then tailored to conform to the final shape of the balloon and consecutive pairs of sheets are sealed together along their length by heat-welding. The heat-welding is carried out by bringing a red-hot nichrome wire close to the sheets, which are held between metal plates; due to the radiant heat the plastic melts and forms a continuous bead. The balloon is thus made out of a large number of sections joined together along their length.

Design: The design of the balloon is governed essentially by the following considerations:

1. The volume to surface ratio should be as large as possible; this is necessary to attain maximum altitude with a balloon of given weight (see equation 1). The sphere is the best shape from this point of view.

2. The tensions in the fabric, (longitudinal tensions arising from the suspension of the load and transverse tensions from the excess pressure of hydrogen), must be suitably distributed to avoid undue stresses in any region; thus for example, for carrying extremely heavy loads, the optimum shape would be an inverted pear.
3. It is known that very considerable stresses occur near the top of the balloon during the filling and launching operations. The stresses arising in the launching are dynamic and are not easily calculable. The design of the top to withstand these shocks has to be determined experimentally.

The design of the balloons at present in use is shown in Fig. 1. The basic shape is the sphere. The top and bottom are, however, conical with a semi-vertical angle of 60°, the cone being continuous with the sphere. The conical top was chosen in place of the spherical because of the following considerations: Firstly, from the point of view of balloon construction, it is difficult to bring together at the top a large number of sections tapering to a point; secondly, during the filling and launching operations it was found that the flat top tends to split.

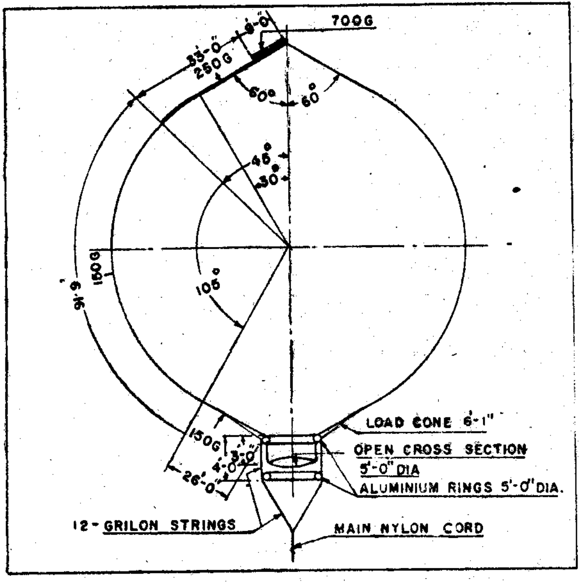


Fig. 1

In order to test the strength of the top a number of static tests were conducted. In these, the balloon was clamped to the ground and hydrogen filled into the upper part until the balloon burst. From these tests it was also found advantageous to make part of the conical top, (upto 9′ slant height), out of thicker polyethylene. The increase in weight when using, for this region, material of thickness ·007″ instead of normal thickness ·0015″, is only 2·7 kgms.; but it adds considerably to the strength of the top. During the acceleration which the balloon undergoes at launch, the top gets flattened out to the shape of a mushroom as a result of the air-resistance. It is generally recognized hat bursts occurring during the launching and mushrooming stages constitute one of the important causes of balloon failure. Since the introduction of the reinforced conical top there has not been one instance of failure during filling, launching or mushrooming.

The bottom cone was designed to allow for complete utilization of volume at ceiling, to facilitate the incorporation of a suitable escape tube and to ensure a proper and natural distribution of tensions in the fabric. The bottom cone, at a circumference of 15 feet, is looped back and has an aluminium ring inserted into it. From this ring, at about a distance of four feet, is suspended another ring by means of parallel nylon strings. The load is suspended from the lower ring. In flight both rings remain horizontal. To allow the excess gas to be thrown out when the balloon attains ceiling, there is a cylindrical escape tube 3 feet in diameter attached to the bottom cone. This tube hangs within the strings connecting the two aluminium rings. The escape tube is kept closed by a pressure-operated valve, which opens it only after the balloon crosses the 100 mb. level. The escape valve and the method of suspending the load is due to the flight group at the University of Bristol, England.

TABLE I

Radius of the balloon in feet	Volume in cubic feet x 10^5	Weight in kgms.	Inflated height in feet	Deflated length in feet	Theoretical ceiling in mb. with no load: outside air temp. 220°A
40	2·68	85	92·3	130	7·5
50	5·24	132	115·5	163	5·9
60	9·05	190	138·8	195	4·9

In the above table are given the various characteristics of the standard balloons which are now being produced and flown.

The flight

Launching: At a point about 50 feet from its top the balloon is clamped by means of a nylon belt to a metal stand. The stand forms part of a double beam weighing mechanism. The upward pull exerted by the balloon on the clamp is balanced by a movable counter-weight. The system has an accuracy of measurement of 200 gms. in 200 kgms. Hydrogen is filled into the top bubble and the total lift is measured by the weighing machine; the true total lift can only be determined in the absence of wind, which would otherwise exert a pull on the balloon; a no-wind condition can be obtained, if necessary, with the use of a wind-breaker. The basic design of this launching platform is similar to that used by the flight group at the University of Bristol, England.

Rate of ascent

From our experiments, the constant K in the rate-of-rise formula (2) is found to be 1100—1150 in the first 10,000 feet of the atmosphere. It appears to gradually increase and attain a value of about 1500 by 45,000 feet. The experiments to determine K have been carried out with balloons made of transparent fabric, so that changes in the rate of ascent due to solar heating of hydrogen can be neglected. The change of K can be explained in terms of the change in the Reynolds number during ascent.

The balloons are flown here with a rate of ascent of about 600 ft/min. On an average flight, with a gross-lift of 200 kgms. the free lift is about 8·5 kgms. *i.e.* about 4% of the gross lift. Because the free lift generally employed is comparatively small, it is necessary to determine the lifting power of the balloon fairly accurately.

Performance in the Troposphere

(i) *Bursts in the Tropopause*

In the initial stages all balloons were made from transparent fabric. This fabric has a coefficient of absorptivity $\alpha \sim 5\%$; the coefficient of absorptivity is defined for solar radiation at ground. It was found that most of these balloons burst between 40,000 and 50,000 feet. These failures were attributed to either the high rate of ascent, (R=1200—1500 ft/min), or cold brittleness of the fabric or to a combination of both. That this was not primarily due to a high rate of ascent became apparent when balloons made to travel very much slower, (R=600 ft/min), also burst at the same altitude. The failures were then pinpointed as being due to low temperature brittleness of the fabric.

(ii) *Low Temperature Brittleness*

It is known that most polymers used for extrusion of polyethylene films have a cold brittle point between —50°C and —60°C. With specially chosen polymers and controlled extrusion the brittle point could be lowered to —70°C. Even so, the definition of brittle point, (according to the standard tests of the American Society for Testing Materials), implies that only 50% of the samples will survive embrittlement at that temperature. In these latitudes, (around 10°N), the temperature of the tropopause is as low as —80°C, which is below the brittle point of the best available material. Furthermore, although the brittle point is to some extent dependent on the degree of orientation present in the film, it is considered generally that there is very little likelihood of achieving much lower brittle point values for polyethylene. Therefore, with balloons of large size, where the tensions are close to the limits which the fabric can stand, the lack of low temperature flexibility makes the probability of survival through the tropopause very small at these low latitudes.

(iii) *Use of Black Polyethylene Film*

Because of these features, it was decided to use coloured fabric which would get heated by absorbing solar radiation. A number of laboratory and flight tests were conducted to fix the optimum absorption coefficient for the fabric in different regions of the balloon. The absorptivity has to be large enough to keep the fabric completely flexible at the lowest temperatures encountered during the ascent whilst not so large as to cause burning of the polyethylene, (which has a melting point of 110°C), at ceiling altitude, where the fabric temperature is determined by the radiation equilibrium. With black fabric and an absorption coefficient $\geqslant 60\%$ it was found that scorching occurred. If the absorption coefficient was less than 15% the chance of survival through the tropopause decreased considerably. On the basis of these tests the optimum values found were: $\alpha \approx 40\%$ for the top one quarter of the balloon and $\alpha \approx 25\%$ for the rest. Black polyethylene film with these absorptivities and to balloon specifications is manufactured locally, under controlled conditions of extrusion by Dominion Plastic Industries Ltd., Bombay. The black film contains carbon black, which is known to be an antioxidant. Owing to the presence of carbon black environmental stress cracking, which polyethylene films are subject to, is also greatly reduced.

Laboratory tests are conducted to measure the tensile strength, tear strength, impact strength and low temperature brittleness of the fabric. Only film which satisfies the minimum requirements is accepted for balloon production. The nature of the various tests, as well as the specifications and the reasons governing them, are matters of detail which are not discussed here.

(iv) *"Rate-of-Ascent Control" Balloons*

Balloons made from black polyethylene ascend at a faster rate than those made out of clear fabric, for the same initial parameters, on account of the heating of the hydrogen. With the absorptivities now being employed, it has been found that there is an increase of about 8-10% in the total lifting power of the balloon by the time it clears the tropopause. It has been stated previously that the value of 'K' (in the rate-of-rise formula), changes from about 1100 near ground level to about 1500 between 40,000-60,000 feet. As a result of the heating and the change in 'K', the balloon enters the stratosphere with a velocity about two and a half times that at which it left the ground. To avoid this rather high rate of ascent, a control balloon is used. A sufficient quantity of hydrogen is put into the main balloon and the control balloon so that the entire assembly can ascend at about 600 ft./min. from the ground. The control balloon is of such a size that the quantity of hydrogen put into it at ground inflates it fully by about 15,000 feet, after which altitude it steadily loses gas through openings in the bottom. The loss of lifting power resulting from the loss of hydrogen from the control balloon is compensated by the increase in lifting power due to the heating of the gas in the main balloon. The increase in the rate of ascent when the balloon enters the stratosphere is then due solely to the increase in 'K'.

(v) *Turbulence in the Tropopause*

In a number of cases it was found that the balloons were subject to severe buffeting in the highly turbulent region between 40,000 and 60,000 feet where the temperatures are also the lowest. The turbulence occurs either in the form of a sudden change of wind direction or wind velocity which results in violent swinging of the balloon; these winds have velocities of the order of 100-150 m.p.h. Only the top quarter of the balloon is particularly affected by this. To enable it to withstand the buffeting, the top quarter is made out of slightly thicker material, (·0025″ thick); as stated before, the first 9′ slant height of the top cone is made out of material ·007″ thick (see Fig. 1). All balloons flown since this modification was introduced have survived highly turbulent conditions. It was also to avoid the possibility of embrittlement under these conditions of turbulence and low temperature that material with an absorption coefficient α about 40% was chosen for the top quarter of the balloon.

Ceiling performance

In Fig. 2 is given the height-time curve of a typical flight. The balloons have been tracked by optical theodolites, (for which the conditions of visibility are extremely good), and by the 400 Mcs Metox rawin receivers of the India Meteorological Department; the necessary rawin transmitters are carried up on the balloons. After the requisite time of floating at ceiling, the load line is cut at a point above the parachute by means of a clock-operated electrical cut off; the equipment is then brought down to ground by parachute. The time of floating depends on the needs of the experiment being conducted and on the prevalent winds; the aim is to have the equipment land on ground in an area where recovery can be effected speedily; this is not necessary in the case of instruments which send all the pertinent observations from high altitude to ground by radio. For successful tracking and speedy recovery it is essential that good communication channels exist between the launching team, the observers along the trajectory of the balloon who man the tracking equipment and the recovery team which is posted in the region where the equipment is expected to land.

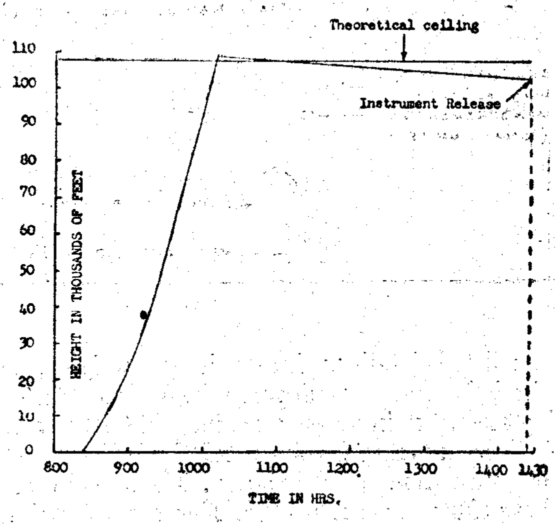
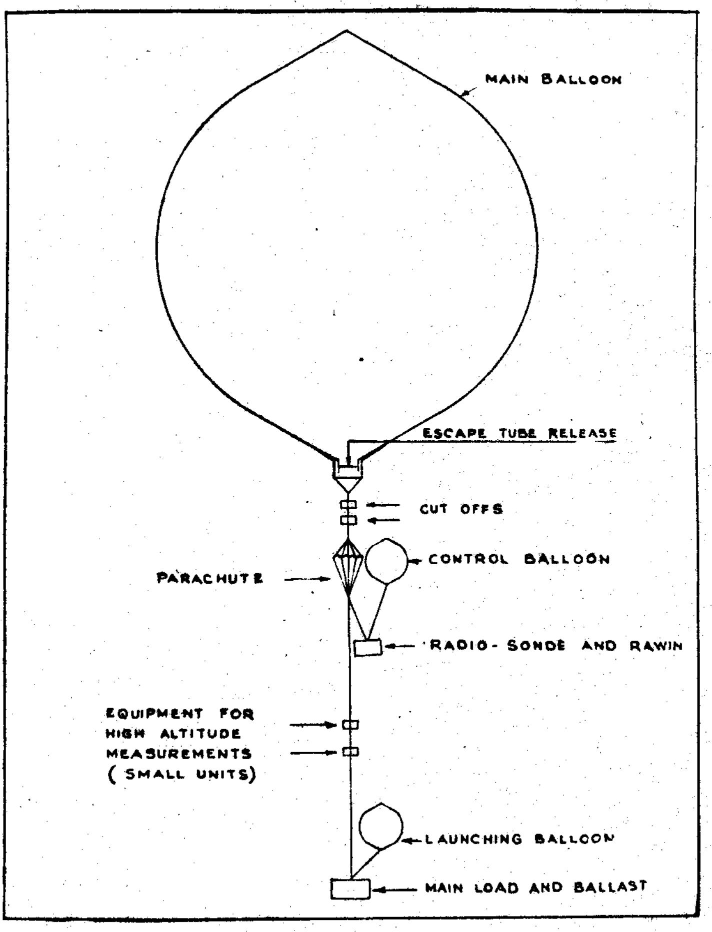


Fig. 2

Measurements of pressure are carried out using bellows and manometers which radio the information to ground by means of 70 Mcs transmitters. Most of these accessories are well known in balloon flying and need not therefore be described herein.

In Fig. 3 is shown a schematic drawing of the balloon and load line.

FIGURE - 1



Economics

In Table II are listed details such as volumes, weights, cost of material used for making the balloons and ceilings attained with different payloads, for balloons of varying sizes, ranging from a radius of 10 ft. to a radius of 90 ft. A rough estimate of the expenses involved and the balloon performance to be expected can be obtained from this tabulation. The actual cost of making the balloon i.e. the labour charges, are not listed. They may be estimated by means of the formula, $CR^2/15W$ which gives the labour charges in rupees for making a balloon of radius R ft. out of material of width W feet when the daily wage is Rs. C/-. Under the present conditions, this works out at a quarter to a fifth of the cost of material used for making the balloon.

The ceiling altitudes given in Table II have been calculated without taking temperature effects into account. They are thus about 15% less than the actual ceilings attained.

TABLE II

Radius in feet	10	15	20	25	30	35	40	50	60	70	80	90
Volume in Cu. feet	$\times 10^3$ 4·0	$\times 10^4$ 1·4	$\times 10^4$ 3·35	$\times 10^4$ 6·5	10^5 1·13	10^5 1·80	10^5 2·68	10^5 5·24	10^5 9·05	10^6 1·44	10^6 2·14	10^6 3·05
Weight in kgms	5	13	21	33	48	65	85	132	190	259	338	428
Approx. cost of polyethylene required for Balloon	Rs. 60	Rs. 150	Rs. 250	Rs. 400	Rs. 600	Rs. 800	Rs. 1,000	Rs. 1,500	Rs. 2,200	Rs. 3,000	Rs. 3,900	Rs. 4,900
Payload kgms	Ceiling mb.											
0	36·7	28·0	18·4	14·9	12·5	10·5	9·2	7·5	6·2	5·3	4·7	4·1
10	110	48·4	27·1	19·4	15·1	12·3	10·3	8·0	6·6	5·5	4·8	4·2
20	183	69·9	35·9	23·9	17·6	13·9	11·5	8·6	6·9	5·7	5·0	4·3
30	..	90·3	44·6	28·4	20·2	15·5	12·6	9·2	7·2	5·9	5·1	4·4
50	..	132	62·0	37·4	25·6	18·7	14·7	10·3	7·8	6·3	5·4	4·6
70	..	174	79·5	46·4	30·5	21·9	17·0	11·4	8·5	6·8	5·7	4·8
100	..	..	106	60·9	39·4	25·8	20·2	13·1	9·5	7·4	6·2	5·1

Acknowledgements

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The programme has been carried out by members of the Plastic Balloon Project and the High Altitude Studies Group of this Institute. To all of these we would like to express our sincere thanks for their whole-hearted efforts and conscentious work on which the programme has been built.