STRATOSPHERIC FLIGHTS OVER TROPICAL LATITUDES WITH POLYETHYLENE BALLOONS OF LARGE VOLUME

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ABSTRACT

Balloons, upto two million cubic feet in volume, made out of locally extruded polyethylene film ·0011 inches thick, have been successfully flown and altitudes of upto 120,000 ft. attained. Instrumented pay-loads upto 100 kg. in weight have been floated at level ceilings around these altitudes. Various aspects, (such as balloon material, shape and design, and launching methods), which relate to the technique of flying polyethylene balloons of large volume over tropical latitudes are briefly discussed.

1. INTRODUCTION

A PROGRAMME of carrying out flights at high stratospheric altitudes with polyethylene balloons of large volume was initiated at the Tata Institute of Fundamental Research in 1956. The objective was to carry up electronic detectors and photographic emulsion stacks to altitudes near the top of the atmosphere, and to keep them at these heights for several hours in level flight, for observations on the primary cosmic radiation. It was clear that, for long term, continuing, and extensive investigations on the high energy cosmic radiation at these latitudes, for which considerable scope exists in India, a readily available balloon facility of considerable magnitude would be required. This, coupled with the fact that balloons for such programmes were not commercially available, made it necessary for us to develop, completely here itself, the various techniques involved. A preliminary report on the work carried out in the initial stages was published in 1958,[1] when the first successful level flights were achieved at altitudes of over 100,000 feet. Since then a large number of flights have been conducted annually for regular research programmes on the primary cosmic radiation, and many improvements have been effected in the technique; in particular, balloons upto two million cubic feet in volume have been flown; altitudes of about 120,000 feet have been attained; instrumented pay-loads up to 100 kgm. in weight have been floated at level ceiling around these altitudes for time periods of 8–10 hours. A great deal of experience has been acquired in the various launching techniques and their applicability to different conditions. In this paper we propose to describe briefly some of these aspects.

2. 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 pressure P, (in millibars), at which the balloon will float, is defined by the equation,

$$\frac{W + L}{V} = (\rho_a - \rho_h) \times \frac{P}{P_o},$$

where

P_o = Sea-level atmospheric pressure in mb.,

W = Weight of the balloon (kg.),

L = Pay-load (kg.),

V = Volume (m^3).

ρ_a, ρ_h = Densities of air and hydrogen (kg./m^3) at pressure P and temperatures T_a and T_h in °K.

The balloons are filled with a gas which is lighter than air, generally hydrogen or helium, for lifting the gross load (W + L); in India, only hydrogen is available as lifting gas. In order to make the balloon ascend, an extra amount of gas, called the free lift '*f*', has to be filled into it. As the balloon ascends, the gas expands and occupies more and more of the available volume. And, when it reaches ceiling altitude the full volume V is utilized, and the excess gas needed for the ascent expelled through one or more open tubes called escape tubes. The number, cross-section, and the position of attachment of the escape tubes are determined basically by the volume of the balloon, the floating altitude, and the expected maximum rate of ascent when it reaches ceiling; it is necessary to ensure that the gas is thrown out rapidly enough as the balloon attains ceiling, so that the development of excessive super pressure, which can result in the balloon bursting, is avoided.

3. Balloon Material

Initially, balloons were made from commercially available transparent polyethylene film about ·0015 inches thick. It was repeatedly observed that these balloons, after launch, behaved normally upto an altitude of about 45,000 feet. Then they were seen to burst suddenly into pieces, while passing through the colder regions of the troposphere, *i.e.*, 45,000–55,000 feet, in which the minimum temperatures in these latitudes range between − 70° C. and − 90° C. These bursts were attributed primarily to the known low temperature properties of polyethylene film, which has a cold brittle point ranging between − 50° C. and − 70° C., depending upon the polymer and the quality of extrusion.

The plastic balloon technique was first developed after the Second World War in the U.S.A. where very extensive flights have been carried out. Most of these flights have been made from middle latitude stations, (around 45° and greater), where the minimum tropospheric temperature is rarely lower than − 65° C. And the balloons have been fabricated out of special balloon grade polyethylene film, tested to withstand embrittlement up to − 70° C., (according to standards laid down by the American Society for Testing Materials).

The problem of tropospheric bursts was solved in our case by incorporating fine mesh carbon black in the polyethylene film during the extrusion process. Using this dark material, with an effective absorptivity of 25% for solar radiation, it was found possible to attain 100% survival in passing through the tropopause. The black pigment, by absorption of solar radiation, keeps the film warmer and more flexible than would be the case otherwise. We have, in our earlier publication,[1] discussed fully the use of dark film for balloon survival in the colder regions of the tropical troposphere.

The use of dark film has, however, some undesirable effects:

(*a*) The balloon experiences a continuous acceleration in the stratosphere due to the increased warming of the gas as more and more of its surface gets exposed to solar radiation. The consequent high rate of ascent close to ceiling altitude is dangerous, since it could lead to balloon burst through development of excessive super pressure. The apparent increase of free lift depends primarily on the absorptivity of the film; it is of the order of 8–10% of the gross lift for an absorptivity of 25%. We have solved this problem to some extent by using one or more small balloons for controlling the rate of ascent. The main balloon is filled with hydrogen equivalent to the gross lift less the expected increase due to heating; the hydrogen needed to make up on the ground the full gross lift is filled into one or two small control balloons attached to the load line; these balloons lose their gas continuously through open tubes during ascent, and are of such size that they lose their free lift by 40,000 feet. The loss of gas from the control balloons is compensated by increase in the free lift of the main balloon due to heating. Thus the rate of ascent is kept within safe limits. It should be emphasised, however, that in carrying out launches with zero, or often negative free lift in the main balloon, there is the potential danger of dragging the pay-load on the ground and difficulty in clearing low-lying objects in case of failure of the control balloons.

(*b*) With these coloured balloons night flights are not possible.

(*c*) The presence of the black pigment makes the floating level sensitive to the prevailing heat radiation incident on the balloon, *i.e.*, direct solar radiation *plus* reflected radiation from clouds, etc. It has been found that if the film absorptivity is in the range 20–25%, the balloons maintain level ceiling from morning to noon, but as the solar zenith angle increases in the afternoon, after about 15.00 hours, they start to descend. This is because the lifting power decreases as the hydrogen cools down.

To obviate these unfavourable features inherent in the use of dark balloons, attempts have been made to use better polymers and improved extrusion, and to reduce absorptivity to the barest minimum consistent with safety in the cold regions of the troposphere. We have succeeded recently in getting satisfactory flights with a mean absorptivity of 10% for ·0011 inches thick film extruded under controlled conditions at Bombay from Union Carbide polymer DFD 6600.

4. BALLOON DESIGN

(i) *General Aspects*

The plastic balloon technique was first developed in the U.S.A. under military contracts and no published literature was (and is even now) available on the subject of balloon design except for very brief notes in books on atmospheric research. The only information available to us when we embarked on this programme was the experience of the Bristol University Group in England. And in particular, there was a publication from this group[2] on the Sardinia expedition in 1954 in which they used cylindrical balloons which had conical portions at the top and at the bottom; the cylinder was attached to the cones by spherical sections.

The main drawback in this design is that the circumferential stress increases from the bottom of the cylinder to its top; also changes of curvature occur at the circular transverse joints; this gives rise to undue stresses in the material. With these defects, as the balloon size and weight of pay-load increases, there is increasing likelihood that the balloon will split along the top cross seam.

(ii) *Our Early Design*

In an attempt to improve this design we replaced the cylindrical part by a sphere, which can then be fitted smoothly (tangentially) to a cone. Figure 1 shows, to scale, the design features of such a balloon. Since it is difficult to estimate reasonably the dynamic stresses in the material during filling and launching operations, we carried out full-scale ground (filling and launching) tests to determine the thickness of the material at the top needed to withstand these stresses; these tests showed that, in addition to using thicker material for the top portion, it was necessary to minimise the number of seals in that part. Figure 1 also shows the double-ring load-suspension system and escape tube attached to the bottom of the balloon. With this type of escape tube, the balloons float at a ceiling much lower than the expected one. This is because of intake of air through the bottom escape tube during the traversal of the balloon through the denser parts of the atmosphere. To avoid this the escape tube had to be kept closed by a pressure clamp which was released only when the balloon was well in the stratosphere. The escape valve and load suspension method just discussed is due to the flight group at the University of Bristol. In our earlier publication[1] there is a full discussion of these aspects.

Experience showed that this design had a number of limitations arising from the top conical portion being always under considerable stress, during filling and launching operations, and throughout the flight; often there were additional stresses due to buffeting after launch or due to wind shear in flight. The presence of two cross seals in the top region, (*see* Fig. 1), in each case between material of different thicknesses, was also not satisfactory, since the strength of the seal was smaller than the weaker element (*i.e.*, the thinner film). Further, it was observed that in several flights, which otherwise had a perfectly normal and satisfactory history, the balloon burst after remaining for a few hours at ceiling, indicating possible weakness in the top design. It was therefore concluded that the load-bearing capacity of a design involving a top cone was limited, because only a small and constant area of material near the top was available for skin loading and had to withstand all the strains throughout the flight. A further difficulty was that there was no possible way to change the top design with increase in the size of the balloon and/or pay-load weight; either of these factors would definitely result in increased loading of the top.

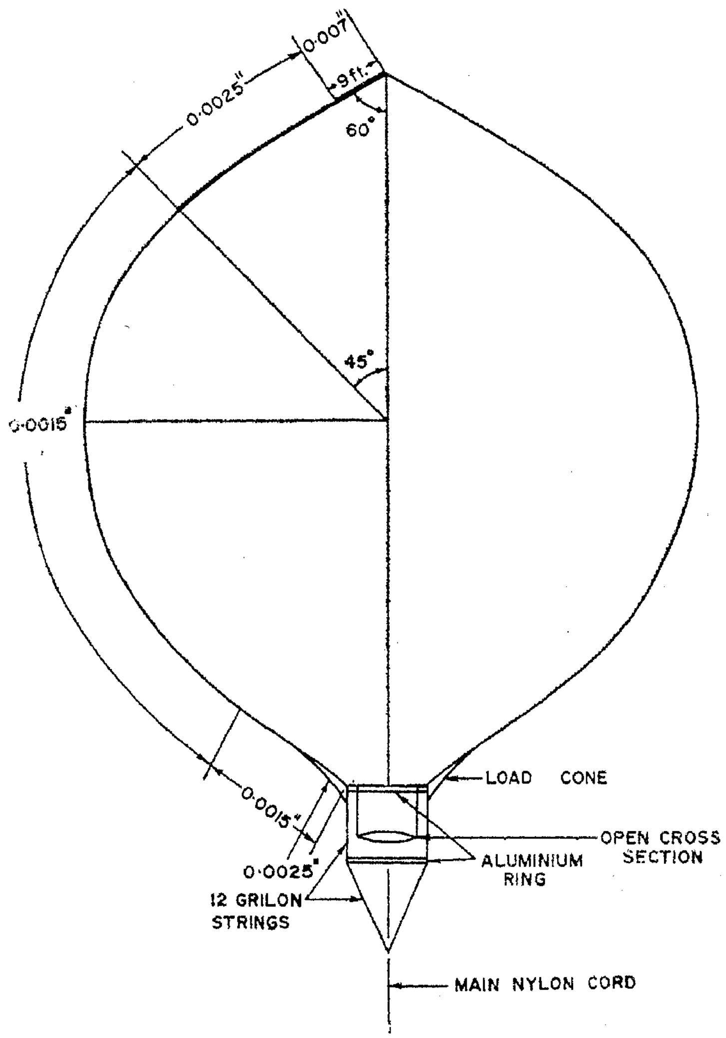

FIG. 1. The early design (cone-sphere-cone shape) with bottom escape tube and load suspension system as discussed in section 4.2; the film-thicknesses used for various parts of the balloon are shown in inches.

(iii) *Present Design*

Attempts were, therefore, made to evolve a design in which: (*a*) there was no need for any cross seals, *i.e.*, in which the material thickness would remain the same from the top to the bottom of the balloon (all along the balloon gore); (*b*) and the cross-section at the top can be related to the gross load.

It was felt that the cone-on-sphere shape was an artificial one based solely on minimising balloon weight and not aimed at a minimal stress distribution; our effort then was to determine the shape which hydrogen gas, without any predetermined constraint on shape, would take under experimental conditions, *i.e.*, when enclosed and loaded as in the case of a balloon.

To obtain the appropriate shape a number of model tests were carried out by inflating cylindrical balloons of moderate size (about 16 feet in diameter) with hydrogen. These models were then photographed. A side tube was provided from the top to the bottom of the balloon to indicate the zero pressure level of the gas inside. Measurements of the following parameters were made on the inflated models:

(1) Maximum diameter (D).

(2) Length, *a*, (along the gore) from the top of the balloon to the plane of maximum diameter; and length *b*, from the latter plane to the bottom, *i.e.*, zero pressure level.

(3) Height (h_1) from the top to the plane of maximum diameter, and (h_2) from the latter plane to the bottom.

An attempt was made to get a close analytical fit to this shape by using different radii of curvature for different parts of the profile which is illustrated in Fig. 2. The values of these parameters (in terms of maximum diameter D as unit) are given in Table I.

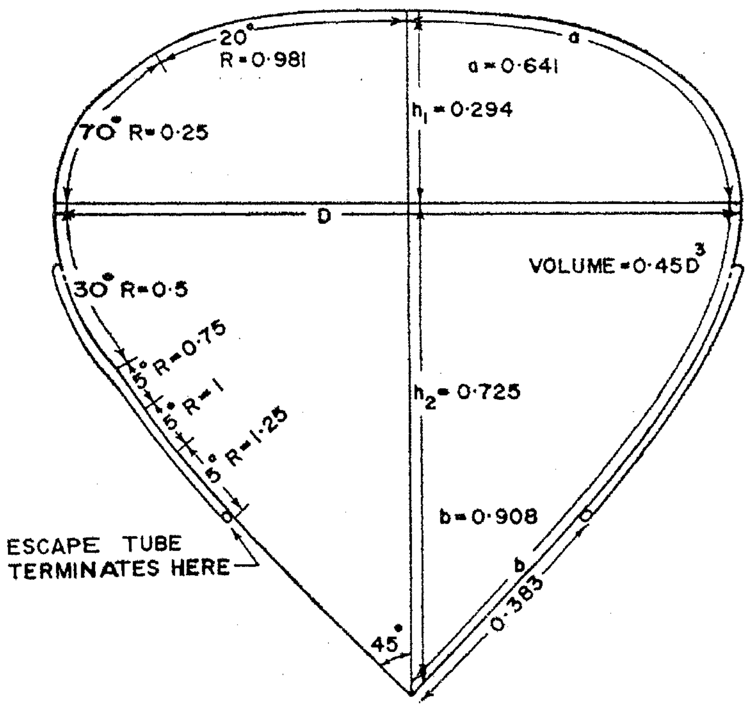

FIG. 2. Present balloon design. The radius of curvature R, in units of the maximum diameter D, applicable to the different parts of the balloon, is shown in the figure.

TABLE I

	h_1	h_2	a	b
Calculated from analytical shape	0·294	0·725	0·641	0·908
Obtained from model tests	0·288	0·715	0·618	0·895

It may be mentioned here that the values obtained above compare very well with those for the balloon designs derived mathematically by the Japanese workers[3] (Table II).

TABLE II

	Deflated length $L = (a + b)$	Maximum radius $= D/2$	Inflated height $= h_1 + h_2$	Volume J
	(all in terms of L as unit of length)			
Derived by Japanese workers	1·0	0·328	0·655	0·120
Our values	1·0	0·322	0·655	0·121

The cross-section of the material to be used at the top essentially depends on the *gross load* whereas that at the bottom depends upon the *pay load*. From Fig. 2, it is clear that there are no cross-seals on the balloon; the gores have the same thickness all along their length. The material at the top and the bottom is symmetrically bunched together and wrapped on an aluminium end-fitting, and clamped with steel strap and felt padding. We have had no failure at ceiling after adoption of this design.

The characteristics of balloons of this shape which have been produced and flown by us are given in Table III. A typical balloon gore for a balloon of volume 2 million cu. ft. is shown in Fig. 3.

(iv) *Escape Tube Design*

The early design of the escape tube (Fig. 1) which necessitated a complicated and unwieldy load suspension and a baro-switch to open the tube in the stratosphere was discarded in favour of one or more escape tubes attached near the top of the balloon. In our design the tube runs all

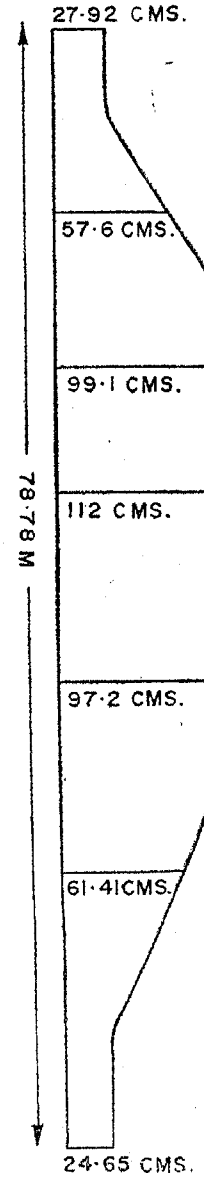

FIG. 3. The shape of the gore for a balloon of volume two million cubic feet.

along a gore to the bottom, where it is cut and kept open at a point which, when the balloon is full, leaves 5% of the total volume as a buffer volume; this obviates any tendency for the development of excessive super-pressure as a result of a high rate of ascent. As the upper end of the escape tube has hydrogen in it throughout the flight there is no possibility of any intake of air into the main balloon; any air that still enters the escape tube through the open end is driven out when the hydrogen expands and escapes through the

TABLE III

Nominal diameter (metres)	Volume $\times 10^3 M^3$	Volume $\times 10^6 ft.^3$	Weight (kg.) for 1·1 mil. film	Inflated height (meters)	Deflated length (meters)	*Theoretical ceiling in Mbs. With no load	With 25 kg.	With 50 kg.
13	1	0·04	15	13·3	20·2	11	28·0	44·0
19	3	0·10	35	19·4	29·6	8·5	15·0	19·0
28	10	0·35	75	28·6	43·5	5·7	7·0	9·0
32	15	0·50	95	32·6	49·8	4·8	6·2	7·0
39	25	0·90	140	39·8	60·6	4·3	5·3	5·7
51	57	2·17	250	52·0	79·4	3·5	3·9	4·1

* Assuming air temperatures as given for a standard atmosphere.[4]

tube. As the escape tube is attached to a gore, it remains folded during the ascent through the denser region of the atmosphere, thus preventing intake of air. Its great length, which is close to the length of the balloon, also prevents any large-scale intake of air. With this type of escape tube one obtains the ceiling which is expected. Figure 4 shows a typical height-time curve for a flight with a balloon of volume 2 million cubic feet.

5. LAUNCHING METHODS

There are three launching methods in use: (i) the clamp method; (ii) the anchor-line method; (iii) the dynamic launch method.

(i) *The Clamp Method*

In the clamp method the balloon is held firmly under a nylon belt at a suitable point from the top leaving enough portion at the top for filling of gas. The rest of the balloon lies folded in a pack on the platform (*see* Fig. 5 *a*). As the gas is filled into the balloon, the lifting power is determined by means of a weighing platform attached to the clamp. The load line, with the various instrument packages, is laid out on the ground with the main (usually heaviest) load at the end. The load line is aligned such that, when launched, the balloon will drift over it picking up the various loads. For

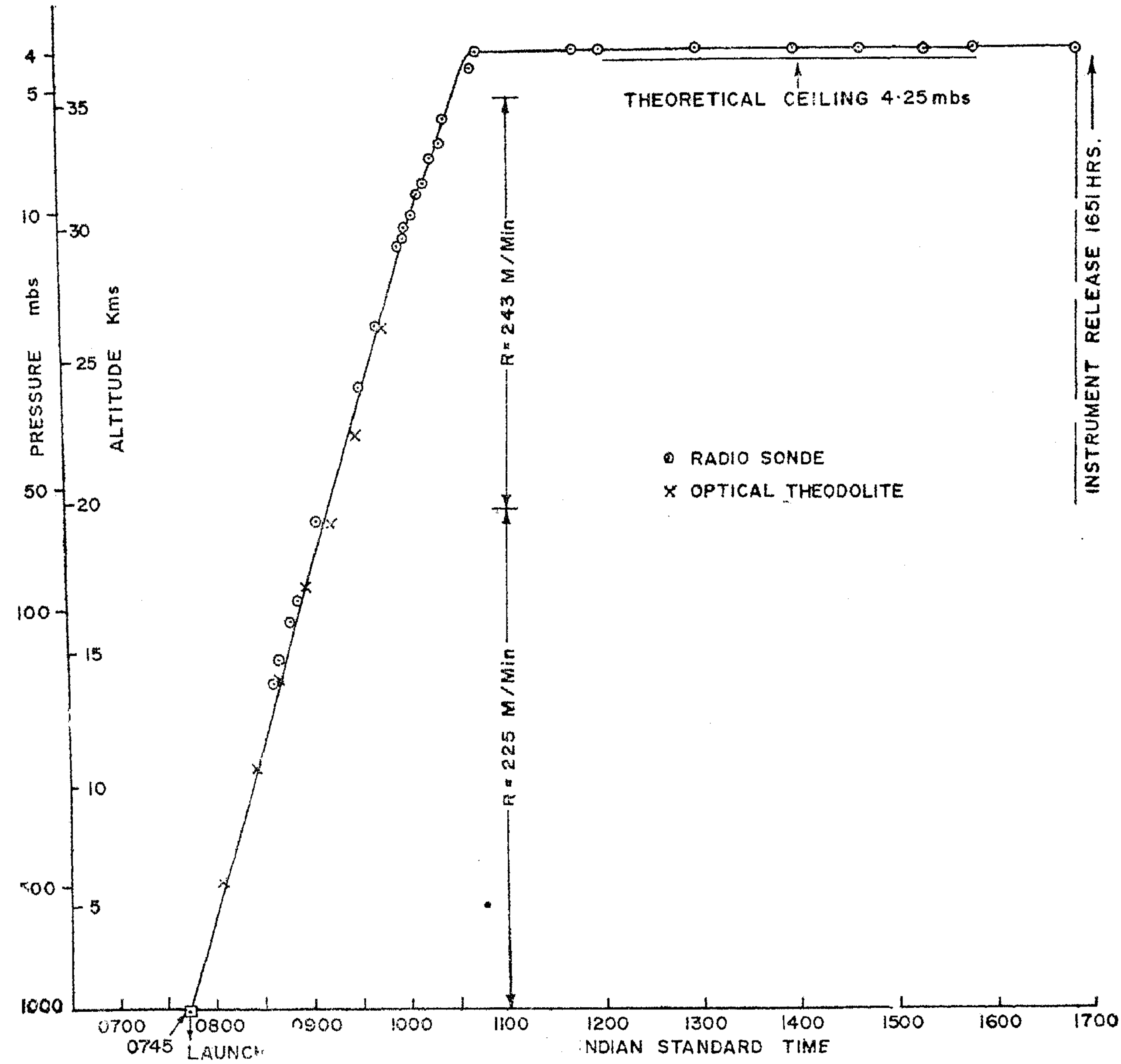

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FIG. 4. Typical altitude-time curve for a balloon of volume two million cubic feet which floated for 6½ hours in level flight; 1·1 mil. film and 323 kg. gross load.

safety, the load line is coupled to the bottom of the balloon only just before launching. The distance between the bottom of the balloon and final package depends on the wind speed—the distance increasing with increasing wind speed.

The balloon is launched by releasing the nylon belt which holds it down. It starts with an acceleration of several *g*'s, since the weight of the top part which is filled with hydrogen (*the bubble*) is only a fraction of the gross load.

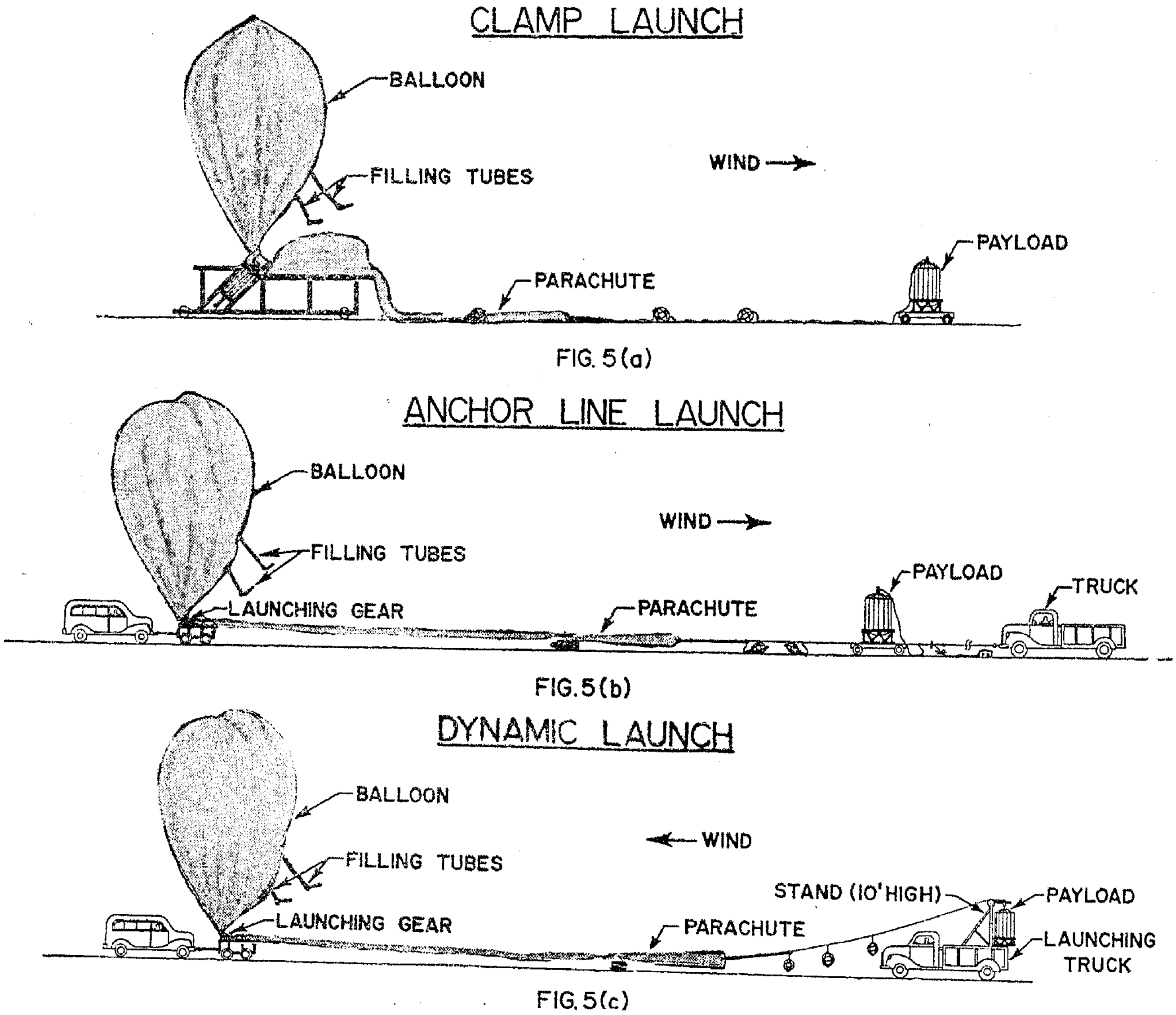

FIG. 5. Different launch methods employed: (*a*) the clamp launch; (*b*) the anchor-line launch; and (*c*) the dynamic launch. In each case the direction of wind necessary for launch is shown.

It is clear that this method has a number of drawbacks. Firstly, the full area of the bubble is exposed to the wind right from the beginning of the filling operation; as a result, in the presence of wind, in the early stages of filling, due to the sail effect, (fanning of the loose material), damage to the balloon can occur, particularly at the point where it is clamped, by pulling through or by flutter; the top of the balloon can even hit the ground. Secondly, it is not possible to measure the lifting power correctly under windy conditions; for using this method, it is necessary to carry out filling operations inside an area shielded from the wind. Thirdly, the '*g*' forces that the top portion has to withstand at launch increase rapidly with increase in gross lift. Hence this method is safe only for launching balloons with small gross loads, *i.e.*, small balloons and small pay-loads. With cone-on sphere design as shown in Fig. 1, we have successfully launched balloons by this method upto 1 million cu. ft., with gross loads upto 320 kg.

Since in this method of launch, the balloon starts with a high acceleration, wl ich is reduced only gradually as more and more material is picked up, it has a high terminal velocity when it picks up the instrument packages and often these are snatched with a large impulsive jerk. To prevent this, one has to use some mechanism on the load line for rapid deceleration. We have used with success open-ended sand bags which are picked up and thus load the balloon but which, whilst in the air, empty in a few seconds; the University of Bristol Group have employed stretchable nylon for the same purpose. We feel that the top enforcement, *i.e.*, use of thicker film at the top, in the cone-sphere design, was primarily necessary to withstand the high '*g*' forces at launch. It would be difficult for balloons made out of ·0011 inches film and of the shape we presently employ (Fig. 2) to stand the clamp launch method in the absence of any enforcement at the top. The clamp method has been used with success for larger gross loads by the Bristol University Group, by carrying out the filling and weighing operation inside a large hanger, and by using a canopy over the top of the balloon which is attached to it and which is coupled to the launch platform. Large *g* forces are avoided at launch by releasing with winches the canopy, and correspondingly the balloon, very gradually.

Gas Meter.—In order to get over the uncertainty in correct weigh-off in the presence of wind, we have been metering the flow of hydrogen gas with a high capacity gas meter (12,000–30,000 feet^3/hour). To relate the volume indicated by the gas meter to the lifting power one needs to know correctly the purity of the gas, its temperature and pressure as it passes through the gas meter, and for this we have carried out extensive calibrations.

(ii) *Anchor-line Launch*

The positioning of the balloon for this method of launch is shown in Fig. 5 *b*. In this, a small portion of the top of the balloon is passed under a roller arm (called the 'Launch arm') mounted on a launch gear; the latter is held firm by a stationary vehicle V_1. The rest of the balloon and load line lies stretched on cloth on the ground in the direction of the wind; the end of the load line is anchored by a strong line about 200 feet long to another stationary vehicle V_2. As gas filling proceeds the bubble draws the rest of the balloon and the load line taut against the vehicle V_2. Gradually more and more material is fed to the bubble by moving V_1 and the launch gear slowly towards V_2; care has to be taken that there is no fast slippage over the roller which can result in damage to the material. Throughout the filling operation the height of the bubble is kept to a minimum and the bubble full; sail effects due to winds are thereby minimised. Safe filling operations can thus be carried out under moderate wind conditions in which filling by the clamp method would be unsafe for the balloon. The balloon is launched by freeing one end of the roller launch arm. As the bubble rises in the air it drifts towards the pay-load under the prevailing wind and picks up, in turn, the remaining part of the balloon, the load line and the pay-load. When the pay-load is airborne to a height of about twenty-five feet, the anchor line is cut by firing a pair of explosive squibs and the balloon with its train ascends freely. Since the bubble continuously pulls at the anchor vehicle with its full lifting power, except for a brief moment when it straightens up immediately after it is free, the '*g*' forces it experiences during launch are quite small; hence no enforcement at the top is necessary. Also, the terminal velocity with which it picks up the pay-load is small because of these small '*g*' forces. The load is thus picked up without any shock. The anchor line launch method, being a static method, becomes difficult to use if there are large changes in wind direction, which may require quick repositioning of the pay-load so as to allow a vertical pick-up; this is particularly difficult in the case of heavy pay-loads. When the bubble-pay-load alignment does not correspond to that of the prevailing wind at the time of launch there are risks that the end portion of the balloon and load line might drag and get damaged on the ground before being fully air-borne. Consider, for example, the extreme case when the wind reverses and it now blows into the balloon from the pay-load end; in this case the balloon will experience a large sail effect which will prevent it from drifting to the pay-load. With such conditions the only solution is to move the pay-load fast enough with respect to the balloon in the direction of the wind and feed it when the balloon is vertically above the pay-load. For this it is necessary to have the pay-load on a vehicle which can be manoeuvred. This in effect is the 'Dynamic Launch' described below.

(iii) *Dynamic Launching Method*

As can be seen from Fig. 5*c*, the basic difference between the anchor line launch and the dynamic launch is in the direction of the wind with respect to the line from the bubble to the pay-load. For the dynamic launch the layout is such that the wind blows from pay-load to bubble. The pay-load is suspended on a launch stand built on vehicle V_2. At launch, as soon as the bubble starts rising the launch vehicle V_2 is driven towards it, and at a speed such that when the balloon and the rest of its train becomes vertical in the air the pay-load is exactly below it; at this stage the pay-load is still attached to the launch stand. Explosive squibs are then fired to snap the line which holds the pay-load to the launch stand. The balloon can then ascend freely, lifting the pay-load which is vertically below it. This method, because of manoeuvrability of the pay-load, enables successful launches to be carried out under widely varying wind conditions and is mostly used for launching heavy loads. The only requirement is that it needs large open spaces in which the launch vehicle can be driven freely. Our launches have been carried out from Newali Airfield, Kalyan, the Begumpet Airport, Hyderabad and the Osmania University Parade Ground, Hyderabad.

The dynamic launching method is excellent for heavy loads in which the pay-load constitutes a large fraction of the gross lift. As the launch vehicle and the balloon both move in the direction of the wind, at the point when the balloon picks up the load from the vehicle, the relative velocity between the pay-load and the balloon is very small. Thus the shock to the balloon and to the pay-load is minimum. This method is therefore to be preferred to the anchor-line launch method for delicate pay-loads.

However, for large balloons with small pay-loads this method is not suitable, since in the presence of wind, the balloon is likely to open out into a large sail. This is because the gross lift is only slightly larger than the balloon weight and the difference is not sufficient to overcome sail effects due to wind. For such launches it is necessary to use the dynamic launching method with the direction of the wind from bubble to pay-load as in the anchor line launch; in this case the prevailing wind helps the balloon to move towards the pay-load. This method is a combination of the anchor line launch and dynamic launch techniques.

6. Concluding Remarks

Since the publication of our earlier paper[1] in 1958 we have carried out 76 ascents with balloons of large volume. On most of these flights cosmic ray detector systems have been carried up—both counter telescopes and nuclear emulsion stacks. The research programmes at this Institute on the primary cosmic radiation near the geomagnetic equator are based on these flights. In addition, meteorological information of value, concerning stratospheric circulation at these latitudes has also been obtained.[5] In this report, we have made an attempt to summarise the experience we have gained in the field of balloon flying through this extensive series of flights which we have conducted at these latitudes.

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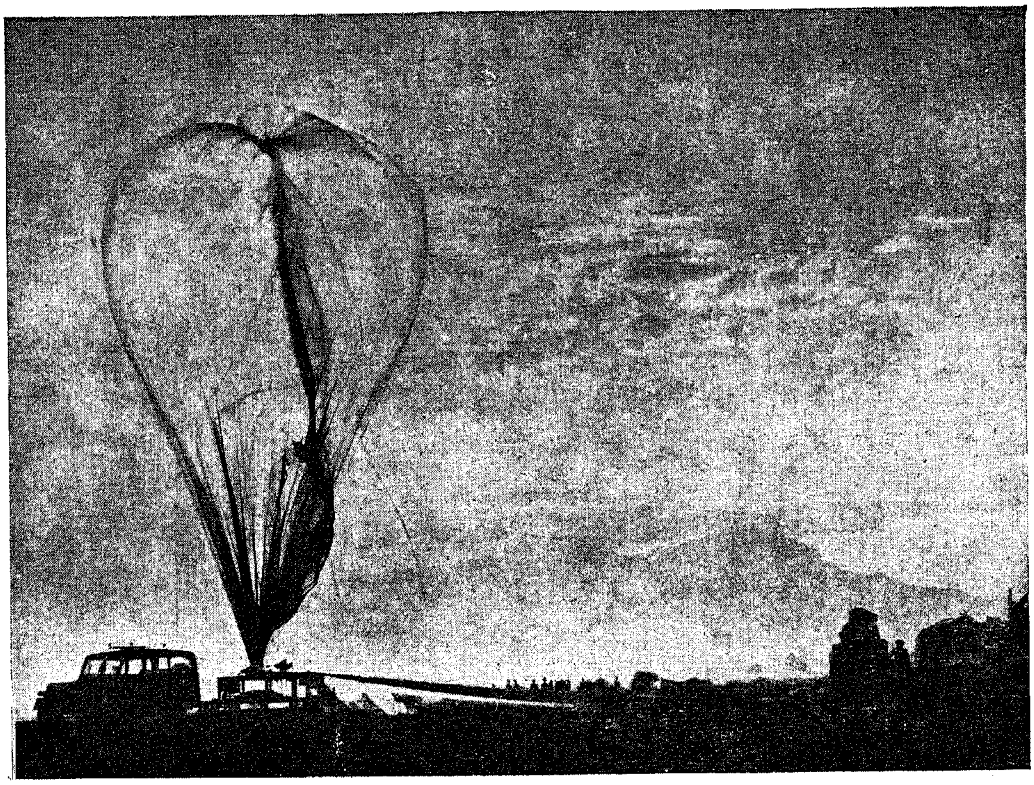
Programmes of this magnitude require large-scale group efforts and we are indebted to members of the Nuclear Emulsion, High Altitude Studies and Balloon Flight Groups of the Tata Institute of Fundamental Research for their wholehearted co-operation.



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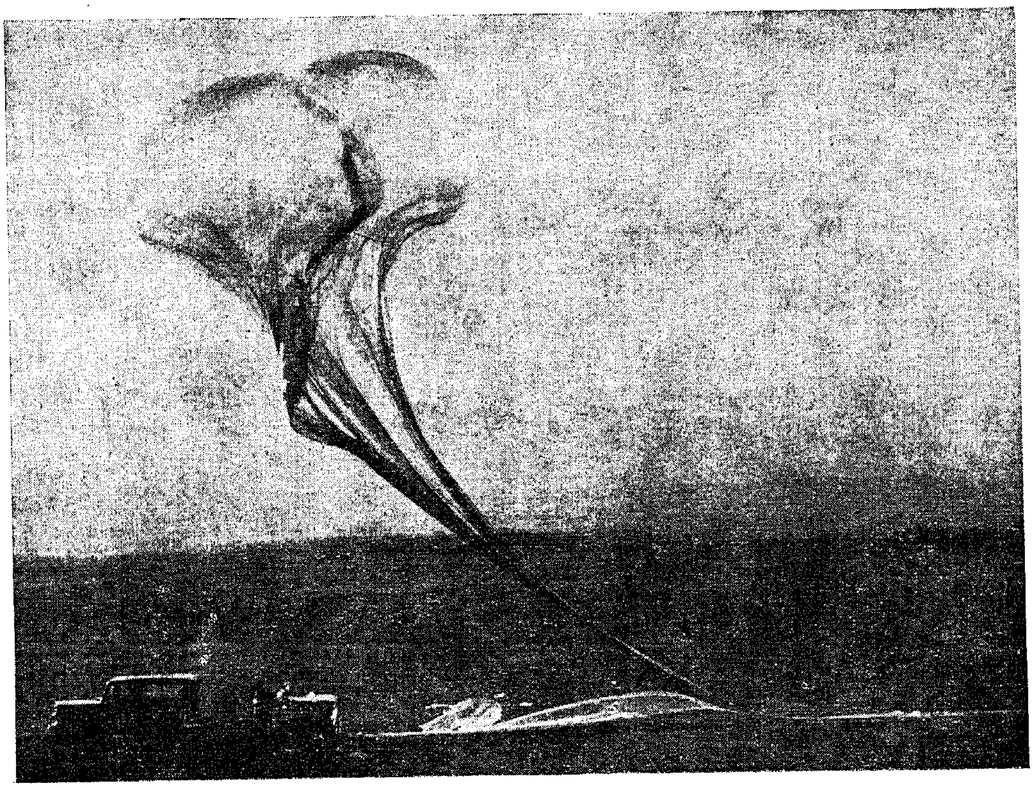

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