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LIZARD BALLOONS

FOR SIGNALLING

THE RATIO OF PRESSURE TO TEMPERATURE.

BY

LEWIS F. RICHARDSON, F. Inst. P..

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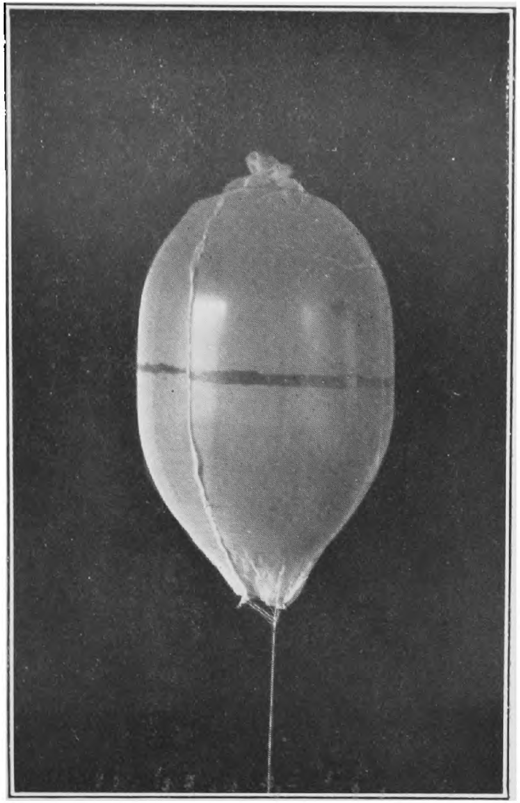

FIG. 1.—Balloon, ready to ascend.

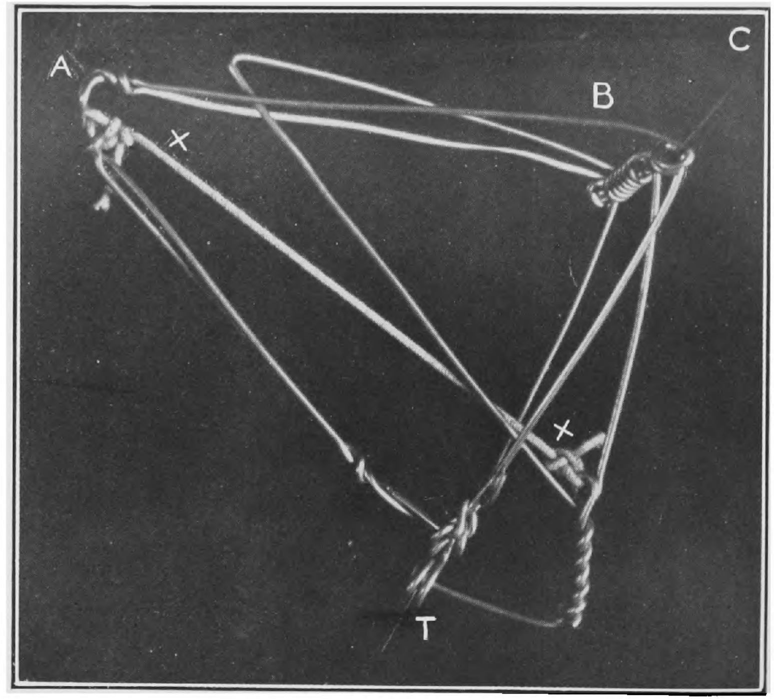

FIG. 2.—Trigger, just open. (Full size.)

B, C mark the ends of the bronze wire which, unfortunately, do not appear in the photograph. The trigger is sewn to the chiffon at A, B, C. The india-rubber spring is marked X X. The tail is attached at T.

LIZARD BALLOONS FOR SIGNALLING THE RATIO OF PRESSURE TO TEMPERATURE.

By Lewis F. Richardson.

§1. General.

The arrangement is shown in Fig. 1. An indiarubber balloon is inflated with hydrogen within an inextensible case of a very light fabric known as chiffon. The balloon drags after it a thread ending in an inverted parachute (not included in the photograph). As the balloon rises its height is observed by measurements of the angle subtended by the tail. The indiarubber, being prevented by the chiffon case from expanding horizontally, expands vertically, and ultimately presses against a trigger, which causes the tail to drop off. Hence the name "lizard," from the habit of some of those animals to drop their tails when disturbed. The initial and final volumes of the indiarubber balloon are compared, just before the ascent, by weighing the corresponding total lifts, so that during calibration the balloon may be likened to a Nicholson hydrometer. In contrast to this, during the ascent the balloon acts as a hydrogen thermometer expanding between known volumes. It therefore measures the ratio of pressure to temperature at the level where the tail is released. Except for the small effect of water vapour it may be said to measure density. Now, Mr. W. H. Dines has shown that the standard deviation of density at heights between 1k. and 5k. is only 1 to 2 per cent. of its mean. Thus if the present instrument is to be of value, it must have a standard error decidedly less than 1 per cent. *A priori* there is some hope of attaining an accuracy of 1 in 1,000, for the working depends mainly upon weighing, and upon the expansion of hydrogen, two processes which are susceptible of very exact treatment. The expansion of the balloon provides ample energy for operating the trigger. But it will be necessary to study quite a number of corrections.

In comparison with "cracker balloons signalling temperature" the lizard balloons signalling p/θ have two advantages and one disadvantage: (i) they are simpler and cheaper, (ii) the quantity p/θ invariably decreases with height, so that the present type of balloon can give us information about inversions of temperature, information which is hardly obtainable by the contact thermometers. But (iii) the contact thermometers promise a higher accuracy of measurement—to 0·3.

§2. Making the Apparatus.

The chiffon had a square mesh, so that it resisted extension in two directions at right angles. One of these directions was

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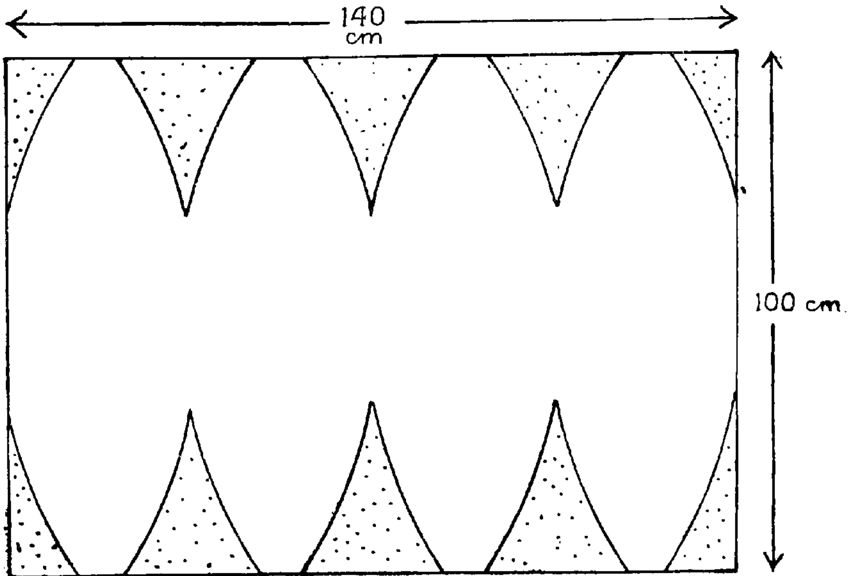
made horizontal. The number of threads was about 35 per cm., and the fabric weighed 13 g. per square metre. Fig. 3 shows the material for the case spread out flat.



Chiffon for a balloon of 90"(=228cm) circumference

FIG. 3.

It is stitched by machine along the curved lines and the dotted portions are cut away. The resulting form is spindle-shaped, which has the advantage that the balloon grips the case firmly in the middle and that the narrow lower end acts like the narrow stem of a thermometer in giving a magnified displacement. Unfortunately it also magnifies the strain on the indiarubber there, so that a balloon must be used having a safe spherical diameter greater than the 140 cm. girth shown in the figure. A balloon having a nominal safe girth of 90 inches = 229 cms. proved strong enough. Possibly a 70-inch balloon would stand the strain if the rubber were of good quality; if so there would be an advantage in using it. To prevent the balloon slipping inside the case, the two are gummed together round the middle (see Fig. 1). A good sticking material is sold under the name of " new skin " for mending cut fingers. It appears to be mainly a solution of collodion in amyl-acetate. It sticks well to the indiarubber without weakening it and the solvent dries off quickly.

The trigger is shown full scale in Fig. 2. It is made from two pieces of aluminium wire, one of phosphor bronze forming the spindle, and one piece of covered indiarubber. The phosphor bronze is used for strength and so that the loops at its ends can be made thread-tight by solder. The indiarubber keeps the trigger closed until the balloon opens it. This very fine indiarubber is used in shops for attaching small objects to cards for exhibition. The whole trigger weighs about 2 grammes. The photograph shows it on the point of releasing the small aluminium plate which forms the upper end of the tail.

The tail.—To prevent the thread untwisting in the air, and thereby increasing its length, it is used double. Then the two parts can untwist only if they also twist up round each other, so the process soon comes to an end. Sewing cotton of size No. 40 appears to be strong enough. Some of it hung up double from the anemometer tower, loaded with 20 g. and allowed to come to rest after twisting and untwisting, was found to have shortened by 3 parts in 1,000, a fraction which is negligible.

The parachute consisted of a piece, 30 cms. square, of a thin but closely woven cotton fabric known as nainsook. It is attached by a thread at each corner.

3. Theory of the Volume-Calibration.

We wish to find the ratio of the volume of the gas when the trigger is just open, to its smaller volume at the beginning of the ascent. The process is rather similar to the use of a Nicholson's hydrometer. The ratio of the volumes would be the ratio of the total aerostatic lifting forces, provided the air density remained unchanged and that the gas inside maintained the same density relative to air at the same temperature and pressure. Actually neither of these conditions can be assumed, and so corrections are necessary.

Let W = weight of empty balloon with case and trigger, in air.

Let L = the "weighed lift," that is the extra weight which will just make the balloon neither rise nor sink when inflated.

Let $W + L = Q$, the total lift.

Then $W + L$ = (weight of air displaced by hydrogen).
—(weight of hydrogen.)

Let s = the specific gravity of hydrogen, relative to air when at same temperature and pressure. It should be noted that for commercial hydrogen s is often 20 per cent. in excess of the value for the pure substance.

The tension of the indiarubber causes the pressure in the gas to exceed the pressure on the balloon by a quantity which we denote by Δp, and which is measured by a water gauge. It is of the order of 10 millibars. The air being at p, and the hydrogen at $p+\Delta p$, the relative density is actually $s(p+\Delta p)/p$. Thus if v is the volume of the hydrogen, and ρ is the density of the air,

$$Q = W + L = \rho v \left(1 - s\,\frac{p + \Delta p}{p}\right) \quad . \quad . \quad . \quad (3{\cdot}1)$$

We observe the weighed lift in still air, and in order to find ρ we simultaneously take the readings of the barometer and of aspirated wet and dry thermometers placed at the level of the centre of the balloon. This is done for the two volumes in succession.

Now let subscript T signify trigger just open,
,, ,, R ,, balloon ready to start, partially deflated.

Then from (3·1)

$$\frac{v_T}{v_R} = \frac{Q_T}{\rho_T} \cdot \frac{\rho_R}{Q_R} \cdot \frac{1 - s_R \dfrac{p + (\Delta p)_R}{p}}{1 - s_T \dfrac{p + (\Delta p)_T}{p}} \quad . \quad . \quad . \quad (3{\cdot}2)$$

If s_R were equal to s_T the formula (3·2) would simplify approximately to

$$\frac{v_T}{v_R} = \frac{Q_T}{\rho_T} \cdot \frac{\rho_R}{Q_R} \left\{ 1 + s \frac{(\Delta p)_T - (\Delta p)_R}{p} \right\} \quad . \quad . \quad (3{\cdot}3)$$

For instance, in one case, $(\Delta p)_T = 11$ millibars, $(\Delta p)_R = 6$ mb, so that as $s = 0{\cdot}08$ the term in curly brackets in (3·3) was $1 + 0{\cdot}08 \times 0{\cdot}005$, and it would be quite unnecessary to include higher terms in the expansion.

It is found, however, that s varies slowly owing to air diffusing into the balloon. The easiest way to correct for this small effect is to observe the change with time of Q/ρ when the balloon, after leaking, is brought back to the fixed volume v_T by the addition of a little more gas. We then correct Q_T/ρ_T to what it would have been at the time of the observation of Q_R. Let $(Q_T/\rho_T - \lambda\tau)$ be this corrected value, where τ is the time interval between the observations T and R. Then our complete formula for the ratio of volumes is

$$\frac{v_T}{v_R} = \left(\frac{Q_T}{\rho_T} - \lambda\tau\right) \frac{\rho}{Q_R} \left\{ 1 + s \frac{(\Delta p)_T - (\Delta p)_R}{p} \right\} \quad . \quad . \quad (3{\cdot}4)$$

§4. Accuracy tested Indoors.

Sensitivity of weighing.—It is well known that the lift of a large pilot balloon can be measured to 0·1g ; say, to 1 in 700 of the total lift. That is in a room. If a special chamber were constructed to screen off draughts, no doubt this accuracy could be considerably surpassed.

Sensitivity of trigger.—For the balloon shown in Fig. 1 it was found that 3mm. motion of the trigger corresponded to 0·2g in a total lift of 87g so that as 1mm. in the motion of the trigger made the difference between open and shut, the trigger was sensitive to 1 part in 1,000 of the volume.

Total lift compared with air density as measured by standard instruments.—Two rooms were maintained at different temperatures, which were measured by an Assmann aspirated thermometer. The balloon was carried from one room to the other and balanced in each. If p_v is the vapour pressure, p the barometric pressure in the room and θ the temperature, then the atmospheric density is taken as proportional to $(p - 0{\cdot}385\ p_e)/\theta$. The operation lasted about half an hour, so that the composition of the gas in the balloon had scarcely time to change. The pressure due to the indiarubber is entered as Δp in the following table, but for the immediate purpose it is negligible. The quantity

$$\frac{(W + L)\,\theta}{p - 0{\cdot}385\ p_e}$$

should be the same in both rooms. It is seen that the agreement is excellent in the first pair. On that occasion the fire in the warm room had been allowed to go out and the chimney had been closed. In the second set the agreement is not so good. The fire was then burning fiercely and, although the balloon was protected from radiation by a screen, there was a difference of temperature of about 1a in the height of the balloon and the temperature was rising. Obviously, calibration should be done in a room without a fire. But an alternative and satisfactory explanation of the difference between 1·760 and 1·754 is found in §11 to be change of relative humidity.

Total lift of balloon. $W + L$. g.	Pressure in room. p. mb.	Aspirated therm. in room. θ. dry. a.	wet.	Vapour pressure p_e. mb.	$\frac{(W+L)\theta}{p - {\cdot}385\ p_e}$.	Pressure due to india-rubber. Δp. mb.	Set.
70·5	995·1	283·0	280·1	8·0	2·011	12·2	I.
68·7	995·4	290·1	286·0	13·1	2·011	11·4	
63·6	1008·2	278·2	277·0	7·3	1·760	13·8	II.
62·2	1008·5	283·5	280·7	8·4	1·754	c 14	

§5. Theory of the Expansion during the Ascent.

In laboratories gas thermometers are worked either at constant pressure or at constant volume. Here the ratio of volumes is fixed, and both pressure and temperature vary. So, because for a gas, $v = \text{const} \times \theta/p$ what we obtain is the ratio of θ/p at the instant when the tail drops off, to θ/p during the last observation indoors. For the final observation of the volume-calibration serves also as the first reading on the gas thermometer.

During the ascent the temperature inside the balloon differs, unfortunately, from the temperature of the surrounding air, exceeding it by an amount which we denote by $\Delta\theta$ and which is studied in detail in §7 and §8 below.

Let suffix i distinguish quantities at the height where the tail drops off.

Then $v_i = v_T$ if the chiffon case has not changed in volume. So if k is the constant in the gas equation, we have

$$(p + \Delta p)_R \, . \, v_R = k\,\theta_R \quad . \quad . \quad . \quad . \quad . \quad (5{\cdot}1)$$

$$\text{also } (p + \Delta p)_i \, . \, v_T = k\,(\theta + \Delta \theta)_i \quad . \quad . \quad . \quad . \quad (5{\cdot}2)$$

whence, eliminating k,

$$\frac{(\theta + \Delta \theta)_i}{(p + \Delta p)_i} = \frac{v_T}{v_R} \cdot \frac{\theta_R}{(p + \Delta p)_R} \quad . \quad . \quad . \quad . \quad (5{\cdot}3)$$

But all the quantities on the right of this equation have been measured during the volume-calibration.

We have so far ignored the leak. During the volume-calibration we were concerned with the leak as effecting a change in the composition of the gas. But when we are dealing with the balloon as a gas thermometer the composition and density of the gas is of no importance, provided we know its volume at a fixed p/θ. Thus we have to do with quite a different aspect of the leak. The simplest plan is to find the amount ζ by which the leak would have reduced the volume, during the interval of time between the observation denoted by a subscript R and the instant when the tail drops off, and then to write in place of (5·3) above

$$\frac{(\theta + \Delta \theta)_i}{(p + \Delta p)_i} = \left(\frac{v_T}{v_R} + \zeta\right) \frac{\theta_R}{(p + \Delta p)_R} \quad . \quad . \quad . \quad (5{\cdot}4)$$

Now ζ has to be found by weighing the lift and noting its change with time. But in order to eliminate the effect of changes in the densities of the air and of the gas, we must study not the raw lifts but the changes of the ratio v_T/v_R, given by the formula (3·4)

$$\text{thus } \frac{v_T}{v_R} = \left(\frac{Q_T}{\rho_T} - \lambda\,\tau\right) \frac{\rho_R}{Q_R} \left\{ 1 + s\,\frac{(\Delta p)_T - (\Delta p)_R}{p} \right\} \quad . \quad (5{\cdot}5)$$

after the balloon has been finally sealed up.

From (5·3) we find the numerical value of $(\theta + \Delta\theta)_i/(p + \Delta p)_i$. Then knowing the small quantities $\Delta\theta_i$ and Δp_i, and having an approximate value of θ_i and p_i we get θ/p exactly, thus

$$\frac{\theta}{p} = \frac{1 + \dfrac{\Delta p}{p}}{1 + \dfrac{\Delta \theta}{\theta}} \cdot \frac{\theta + \Delta\theta}{p + \Delta p} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5{\cdot}6)$$

Let us now study Δp and $\Delta\theta$.

§6. Temperature Coefficient of Pressure due to Rubber Δp

Measurements on a balloon, inflated inside a chiffon case, connected to a water-gauge, and adjusted by means of the trigger to be always in one position, gave the result *that* Δp *increased by* 1·1*mb per* 10a *fall of temperature, between* 278a *and* 294a. It is seen that the effect is quite a small one, so that it will be sufficient to make a guess at the upper air

Then $v_i = v_T$ if the chiffon case has not changed in volume. So if k is the constant in the gas equation, we have

$$(p + \Delta p)_R \,.\, v_R = k\,\theta_R \quad . \quad . \quad . \quad . \quad . \quad (5\cdot1)$$

$$\text{also } (p + \Delta p)_i \,.\, v_T = k\,(\theta + \Delta\,\theta)_i \quad . \quad . \quad . \quad . \quad (5\cdot2)$$

whence, eliminating k,

$$\frac{(\theta + \Delta\,\theta)_i}{(p + \Delta\,p)_i} = \frac{v_T}{v_R} \cdot \frac{\theta_R}{(p + \Delta\,p)_R} \quad . \quad . \quad . \quad . \quad (5\cdot3)$$

But all the quantities on the right of this equation have been measured during the volume-calibration.

We have so far ignored the leak. During the volume-calibration we were concerned with the leak as effecting a change in the composition of the gas. But when we are dealing with the balloon as a gas thermometer the composition and density of the gas is of no importance, provided we know its volume at a fixed p/θ. Thus we have to do with quite a different aspect of the leak. The simplest plan is to find the amount ζ by which the leak would have reduced the volume, during the interval of time between the observation denoted by a subscript R and the instant when the tail drops off, and then to write in place of (5·3) above

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Now ζ has to be found by weighing the lift and noting its change with time. But in order to eliminate the effect of changes in the densities of the air and of the gas, we must study not the raw lifts but the changes of the ratio v_T/v_R given by the formula (3·4) thus

$$\frac{v_T}{v_R} = \left(\frac{Q_T}{\rho_T} - \lambda\,\tau\right) \frac{\rho_R}{Q_R} \left\{ 1 + s\,\frac{(\Delta\,p)_T - (\Delta\,p)_R}{p} \right\} \quad . \quad (5\cdot5)$$

after the balloon has been finally sealed up.

From (5·3) we find the numerical value of $(\theta + \Delta\theta)_i/(p + \Delta p)_i$. Then knowing the small quantities $\Delta\theta_i$ and Δp_i, and having an approximate value of θ_i and p_i we get θ/p exactly, thus

$$\frac{\theta}{p} = \frac{1 + \dfrac{\Delta p}{p}}{1 + \dfrac{\Delta\theta}{\theta}} \cdot \frac{\theta + \Delta\theta}{p + \Delta p} \quad . \quad . \quad . \quad . \quad . \quad (5\cdot6)$$

Let us now study Δp and $\Delta\theta$.

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§7. Radiation Correction.

For research purposes the warming of the balloon by sunshine may be measured reliably by the increase in lift, or by the motion of a trigger, or by change of the internal pressure, if the two last have previously been calibrated against change of lift. But in the course of routine ascents some quicker and handier process will be required. For the latter purpose I have used a black bulb thermometer placed in a measured wind and have noted its excess above an Assmann aspirated thermometer at the time of the ascent. It remains to find the relation which the warming of the balloon bears to that of the black bulb, not forgetting the velocity of the balloon nor the density of the air aloft. The particular black bulb used was an ordinary mercury thermometer having a spherical bulb about 1·0cm. diameter. The bulb and the adjoining stem were coated with carbon ink (Messrs. Winsor and Newton's " Mandarin black "). On account of its permanency this simple thermometer was preferred to the usual type in an evacuated case.

Experiment 1.—A comparison in nearly still air was carried out in the beam of sunshine streaming through the open door of a hut. The balloon was undyed, of nominal circumference 70 inch (=178cm.) and was inflated within a white chiffon case so as to be in contact with the chiffon except near the ends. Other experiments have shown that a thermometer inside the balloon rises if the balloon, while exposed to sunshine, shrinks away from the chiffon. The mass of the balloon was 22·9g., that of the chiffon and trigger 10·6g. Owing to the draughts from the open door, it was not possible to weigh the lift with an accuracy beyond that corresponding to 0·5a. Eleven observations were made, the lift being weighed alternately in the sun and in the shade, but always at the same level as the black and aspirated thermometers. Here are the results. Air temperature 284a, pressure 1018mb, both in the hut.

—	a.	a.	a.	a.	a.
Black bulb exceeds aspirated ...	8·9	7·1	10·0	8·0	8·4
Balloon exceeds air temperature	3·9	3·7	4·6	5·1	4·3

Subsequent experiments indicated that the variations of Δp were not negligible, and an allowance of 10 per cent. has been made for this below.

The last three observations were in bright sunshine at 1920 May 10d. 8h. G.M.T. The mean result is that *the temperature of the undyed balloon exceeds that of the air by* 0·55 *of the excess of the aforesaid black bulb over the aspirated, both being in nearly still air.*

Experiment 2.—A number of readings of a bright mercury thermometer placed inside a balloon inflated with hydrogen inside a white chiffon case, when compared with those of the aforesaid black bulb and of the aspirated thermometer, all at the same level in the open, showed that for both bright and dim sun and for various velocities between 0 and 2 m/s, the excess of the thermometer in the balloon over the air temperature was about 0·9 or 0·8 of the excess of the black bulb over the air temperature, according as the balloon was dyed red or undyed. The thermometer in the balloon is to be regarded as indicating an upper limit to $\Delta\theta$, for the thermometer itself absorbs a good deal of the diffuse sunshine which passes through the balloon. This upper limit confirms the measurements made by weighing the lift.

Experiment 3.—A balloon, tightly inflated with hydrogen inside a chiffon case, was carried in and out of the shadow of a roof. The balloon was nearly touching the trigger, so that its expansion on warming was visible and the successive positions of the indiarubber were noted in the field. At the same time the aforesaid black bulb was read both in the sun and in the shade and was compared with an aspirated thermometer. Also the wind-speed was measured at the same level by a Dines air-meter. Immediately afterwards, in the laboratory, the volume and pressure of the balloon were measured at the various positions of the indiarubber observed in the field. The positions were attained by letting hydrogen in or out. The volumes corresponding to the different positions were compared by weighing the total lifts; and the pressures Δp noted on a water gauge, the barometer being steady. From the volume and pressure changes, and the Boyle-Charles equation, it followed that the balloon was 1·7a warmer in the sun than in the shade. The excess of the aforesaid black bulb over the aspirated thermometer was 3·2a in the sun and roughly 0·8a in the shade. So the temperature change of the balloon was $1{\cdot}7/(3{\cdot}2 - 0{\cdot}8) = 0{\cdot}71$ of the change of this black bulb.

The relative velocity of balloon and air was 3·6 metres per second. The balloon was an undyed one of 90 inch (= 229cm.) nominal circumference, and weighed 35 grammes when empty. The chiffon case was white, had a " tuck " round its equator, which made the material 3 layers thick in a belt 8cm. wide. The weight of the case was 14g. Total lift about 71g. weight. Air temperature 288a pressure 1012mb. Bright sunshine on May 13d. 15h. local time in latitude 52°N.

Experiment 4.—Measurements such as the preceding in a wind are uncertain because of the strain and vibration in the case.

A more satisfactory procedure is as follows. The pressure Δp due to the rubber, varies with the volume, especially when the balloon is expanding in a conical chiffon neck. This Δp is observed in the field and the volume changes to correspond are found by weighing indoors. The temperature changes of the balloon are then calculated from some arbitrary standard. An allowance is made for the effect of the varying temperature of the aspirated thermometer, both on the black bulb and on the balloon. Both sets of readings are then plotted against time and the drift of the balloon's computed temperature, produced by leak, is eliminated by drawing a base line through the balloon temperatures corresponding to some fixed value of "black *minus* aspirated." The deviations from these two base values are then plotted against one another. The relation was found to be nearly linear and expressible as $\Delta\theta = 1{\cdot}0$ "black *minus* aspirated" This refers to the same balloon as that used in the preceding experiment but now placed in a wind of 2·2 m/s on a May afternoon with variable sunshine.

Summary.—Let us now summarise the observations of $\Delta\theta$. The black bulb is exposed to the same wind and radiation as the balloon.

Colour of balloon in white chiffon.	Method.	Multiplying Factor to obtain $\Delta\theta$ from "Black *minus* Aspirated."	Speed. m/s.	Air density. g/litre.	Remarks.
Red ...	Thermometer inside.	0·9	0 to 2	1·23	Upper limits.
Undyed ...	Thermometer inside.	0·8	0 to 2	1·23	Upper limits.
"	Weighing	0·55	<0·1	1·24	
"	Volume changes.	0·7	3·6	1·21	Rough observation.
"	Δp	1·0	2·2	1·22	

The black bulb is such as anyone can make by coating a spherical bulb 1·0 cm. diameter and the stem adjoining it with Mandarin black ink (Winsor and Newton).

Remembering that some of the observations are upper limits, we may combine them in this working rule: *Expose a black bulb of the kind described so that it receives the same radiation as the balloon, and adjust its height above ground so that the air speed times the density is the same as the ascensional velocity of the balloon multiplied by the density at the height where the tail drops off, then $\Delta\theta$ for the balloon will be 0·75 of black-minus-aspirated if the balloon is rising 175 m/min or 0·55 of the same if the speed is very slow. That is for an undyed balloon. For a red balloon increase $\Delta\theta$ by 10 per cent.*

It must be admitted that this working rule is open to improvement.

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It must be admitted that this working rule is open to improvement.

§8. Lag.

On bringing the inflated balloon from a cold room into a warm one and observing the motion of the trigger, it was found that all but 1/2·71 of the total motion was accomplished in a time of about 35 seconds. That is in still air. By warming the balloon in a room and then running with it across a field it was estimated that the corresponding time was 20 seconds at an air speed of 4 metres per second. These numbers refer to a balloon dyed red, enclosed in white chiffon. So the lag is rather less than that of the contact thermometers of petrol in glass described in a separate paper.

Denote by T the time required for the excess of temperature to fall to $1/e$ of its initial amount, then the equation of cooling is

$$\Delta\theta + \theta - \theta_m = T\frac{d\theta_m}{dt}$$

where θ_m is the temperature of the balloon, $\Delta\theta+\theta$, the temperature which the balloon would have attained if kept for a suitably long time in the same surroundings. For a balloon rising steadily under constant radiation, $d\theta_m/dt$ will be nearly equal to the rate of change of temperature of its surroundings. The correction $Td\theta_m/dt$ amounts only to about 0·4a under ordinary circumstances. Mr. W. H. Dines points out that the gas inside the balloon is cooled by its expansion, so that if the whole thermal capacity of the balloon resided in the hydrogen, the result would be that the lag would be zero if the atmosphere were in adiabatic equilibrium, while the ascending balloon would tend to be colder than the air under actual average conditions. The thermal capacity however is distributed as follows in an actual example :—

		Cal. per g. per 1°C.	Water equiv
Indiarubber 32 g.	at say ...	0·4	13
Chiffon 18g.	,, ...	0·5	9
Cork 1g.	,, ...		0·4
Aluminium 2 g.	,, ...	0·2	0·4
Hydrogen 6g.	,, ...	3·4	20

So about half the thermal capacity resides in the hydrogen, but it is the half less accessible to the temperature of the outer air.

It is evident that the lag must ordinarily be less than 0·4a; just how much less we cannot say without going into the question elaborately. Until that is done, the lag may be neglected.

§9. Accuracy of Height Measurements with a Tail.

The main error here is the casual error due to reading the swinging tail against an eyepiece graticule. We have used parachutes made of nainsook for the tail and it is thought that they swing about less than does paper. Strange to say they do not delay the balloon (C. J. P. Cave and J. S. Dines found that loading a pilot balloon makes it rise more rapidly).*

The casual error of a single observation may be estimated by plotting the observed height against time, drawing a very smooth curve (nearly a straight line) through the observations, and working out their standard deviation from the line. Thus we find :—

Date.	Standard Deviation of height (single observation).	Angular elevation.	Range of height.	Length of tail.
	m.		k.	m.
31.3.1920	33	21° to 12°	0·4 to 1·7	12·4
2.1.1920	39	38° to 16°	0·3 to 1·6	4·5
30.4.1920	16	5° to 9°	0·1 to 0·7	10·3

Part of these variations are no doubt due to eddies. But let us assume the worst case, that they are all observational error. Of course, the height at which the tail drops off is to be deduced from the time, using *all* the preceding observations. Its standard error must be less than that of a single observation, but more than the standard error of their mean. Probably 25 metres is a fair estimate of the standard error at a height of 1·5k. Now 25 metres at this height corresponds to 0·27 per cent. of the density there, where the standard deviation of the density averages 1·5 per cent. Thus in the matter of height measurements we may expect to have errors amounting to $\frac{1}{5}$ or $\frac{1}{6}$ of the natural variation of the quantity we aim to measure. That is rather much, but, in view of the shortage of observational methods, may be permissible. Improvement would be expected to follow practice. Although the azimuth and altitude need only be read every minute, it would be better to observe the tail every 30 seconds.

§10. The Leak.

There is evidence that as hydrogen leaks out from a good rubber balloon, air leaks in

We may measure the leak in two quite different ways :—

(i) By observing the change in the lift with time while the neck of the balloon is closed and the volume gradually diminishes. (*See* ζ in §5),

(ii) By bringing back the balloon to a constant volume, defined by the chiffon case and trigger, by adding from time to time small quantities of gas from the cylinder from which the balloon was originally filled, and we may observe the lift at this definite volume (*see* λ in §3).

Let us consider now only the second of these aspects of the leak. We have as in (3·1)

$$\frac{Q}{\rho} = r\left(1 - s\,\frac{p + \Delta p}{p}\right)$$

* *The Rate of Ascent of Pilot Balloons.* Q.J. Roy. Met. Soc., Vol. xlv., p. 297, 1919.

Here v is fixed, so is the small correction Δp. So if Q/ρ varies it must be because the relative density s of gas to air varies at the same temperature and pressure. The following measurements were made on a 90 in. rubber balloon dyed red and of excellent quality.

Day.	Remarks.	Q/ρ in arbitrary units at fixed volume.	s.
0	Filled	—	0·08
1	After adding a little Gas ...	2·01	0·145
5	Balloon much shrunk, added more gas, afterwards ...	1·76	0·25
5	After emptying and refilling	2·16	0·08

Neglecting the small correction Δp, the figures Q/ρ must be proportional to $1-s$. For commercial hydrogen s is probably about 0·08. If we assume this value to correspond to Q/ρ on the 5th day we get the other values of s in the last column.

For the scientific aspect of the leak, the reader should be referred to thorough studies such as that by H. A. Daynes.*

§11. Constancy of the Chiffon.

A strip, cut at right angles to the selvedge, and stretched under a load of 140g wt per centimetre of width (the maximum stress due to the balloon is about of this order), elongated 1·3 per cent. with this load. It elongated a further 3·5 per cent. when wetted, and at the same time it contracted sideways. Drying hardly changed it, the load being constant. A second wetting caused a further elongation of 0·5 per cent., a third wetting only 0·2 per cent. The main effect of the water is apparently to soften the threads and so to allow those under tension to pull out straight, by crumpling the cross threads.

A strip is not a suitable form of test piece, for what we want to know mainly is the change of area. Instead of cutting a strip, a piece of chiffon was laid over the horizontal mouth of a large stoneware vessel and was cemented to the rim by shellac, so as to form a kind of drumhead. The chiffon was strained by placing a load at its centre. The free part of the chiffon was thus a ring having an inner diameter of 4·8 cm and an outer diameter of 20·9 cm. The load gave the ring a slightly dished form, not quite conical, but rather trumpet-mouthed. The central load carried two pieces of ruled paper which made it possible to read off the separation h of the planes defined by the inner and outer circumferences of the chiffon ring. If a and b are the inner and outer radii of the ring, the area of the ring bears to its area when flat the ratio $1 + \frac{1}{2}\left(\frac{h}{b-a}\right)^2$ approximately.

* *The Process of Diffusion through a Rubber Membrane.* Proc. Roy. Soc. A, Vol. 97, 1920, p. 286.

Time. G.M.T.			Load. g.	Temperature of chiffon. a	Relative humidity. %	h. cm.	Area on an arbitrary scale $=1+\frac{1}{2}\left(\frac{h}{b-a}\right)^2$
d.	h.	m.					
13	10	0	373	—	Dry	1·38	1·015
		1	373	—	Wetted	1·55	1·018
		7	373	—	Wet	1·7	1·022
		17	373	—	Wet	1·95	1·029
		35	373	—	Wet	2·0	1·031
	14	22	373	287·5	57	1·77	1·024
		26	373	—	Wet	2·00	1·031
		40	373	—	Wet	2·00	1·031
	16	3	373	289·2	61	1·80	1·025
14	8	25	373	286·5	60	1·81	1·0252
	13	30	373	289·8	57	1·81	1·0252
	17	20	373	288·8	61	1·84	1·0261
	21	40	373	284·8	70	1·86	1·0267
	22	20	373	284·1	71	1·86	1·0267
15	11	30	373	290·0	52	1·79	1·0247
	Here load decreased.						
		35	25	290·0	52	1·69	1·0220
	Original load restored.						
17	8	30	373	285·3	77	1·91	1·0282
	Here the load received an accidental jog.						
	10	30	373	286·2	78	1·97	1·0299
	14	40	373	287·6	69	1·97	1·0299
		45	373	284·7	Wet	2·09	1·0337

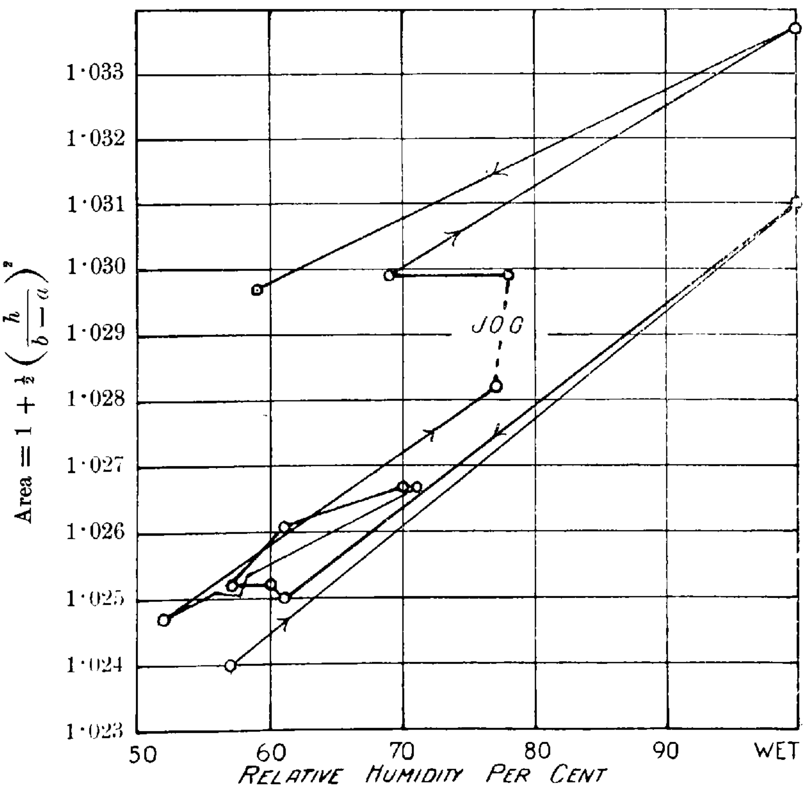

FIG. 4. The Effect of Humidity on the Area of a Chiffon Membrane.

The table shows the permanent accommodation which takes place at the first wetting. It would probably be a good plan to wet each chiffon case while stretched by the balloon, and to let the chiffon dry thoroughly before beginning the calibrations. The subsequent history of the test piece is one of a slow yielding under load, at a rate so slow as not to come into balloon observations, accompanied by an expansion with wetness. The latter amounts to about 0·13 parts per 1,000 of *area* per 1 per cent. change in the relative humidity. In sign it is opposite to the behaviour of a tent in showery weather, but agrees with the behaviour of the human hair hygrometer. It will be more convenient to state it as a change in the *volume* of a chiffon case: *One per cent. increase in the relative humidity increases the volume contained within a chiffon case under constant pressure by* 0·20 *parts per* 1,000. We may also estimate this change from the weighings of the lift of a balloon in hot and cold rooms (§4 above). Thus in the second set, on p. 79, the humidity changed from 84 to 67 per cent., and the corresponding volumes of the balloon, on an arbitrary scale were 1·760 and 1·754. This, for one per cent. increase of humidity, implies an increase of 0·2 parts per 1,000 on the volume, in agreement with the drumhead tests.

If we have any means of guessing the difference of the relative humidity between the room in which the balloon is calibrated and the place where it drops its tail, we can apply the above small correction. Unfortunately the variations of humidity are very irregular. On the average relative humidity decreases with height (Hann, Meteorologie, 1915, p. 234), but just below clouds it must obviously increase.

One might perhaps replace the chiffon by a net made of aluminium wire woven in meshes about 15 cm. across.

The effect of humidity on the mass of the chiffon only concerns us if the humidity varies during the calibration indoors. A piece of chiffon was weighed after exposure to various humidities which were measured by an aspirated wet-and-dry bulb. It was found that *an increase of* 1 *per cent. in the relative humidity increased the mass by* 0·8 *per thousand*, in the range between 44 per cent. and 63 per cent. of humidity. The chiffon has hitherto made up about 0·3 of the total lift. So 1 per cent. of relative humidity increases the total lift by 0.24 per thousand. *The increase of mass thus nearly compensates the increase of volume.* Ordinarily, in calibrating, we may neglect them both. Prof. A. J. Turner has been good enough to give his opinion in the following terms:—

REPORT by Prof. A. J. TURNER, Professor of Textile Industry at the College of Technology, Manchester.

So far as I know there is no textile material which neither expands nor contracts when moistened. The sample of chiffon is a silk material—all silk materials expand on being moistened. Cotton and linen fabrics contract on being moistened : other things being equal, the contraction of linen is less than that of cotton, and, generally speaking, in all cases where it is desirable to avoid changes in dimensions through moistening, it is best to use a linen material.

It would not be possible, I am afraid, to obtain a linen fabric of so fine a texture as this chiffon ; a linen fabric of about half as many threads per inch and twice as coarse (and, therefore, of about the same weight) could I think be obtained from a fine linen manufacturer. If this would serve the purpose, it would be better than the chiffon.

(Signed) A. J. TURNER.

§12. First Ascent 1920, April 30, at Benson.

OBSERVERS : J. A. Gaunt, B. C. Lewis, L. F. Richardson.

The chiffon case was the one shown in the photograph, but it had been mended after a rupture, and had been strengthened by an additional belt of chiffon 8cm. wide round its equator. The tail ended in a parachute (or should we call it a parascent?), made of a piece of nainsook 30cm. square and weighing 6 grammes.

	grammes.
Mass of chiffon and trigger	19·92
Mass of balloon, "90 inch," red	31·88
Mass of cork, stopper and wire hook	1·01
Total	52·81
Tail and parachute	about 6·
	59·

The following exact weighings to determine the ratio of volumes were made in a hut which had no fire. The windows were frequently opened, and fresh air admitted to remove hydrogen or carbon dioxide. In order that the strain in the chiffon during calibration might be as nearly as possible the same as during the ascent, a considerable part (17·92 grammes) of the load required to balance the lift was arranged as a coil of wire, put over the balloon like a belt just above its equator. The neck of the balloon was upwards, and the residue of the load, consisting of a pan and weights, was hooked on to the frame of the trigger below. Aspirated wet and dry thermometers were kept going and were placed at the level of the centre of the balloon, for considerable differences of temperature may exist at different levels in the same room.

The air densities are taken as proportional to $(p - \frac{3}{8}p_e)/\theta$ where p_e is the pressure of aqueous vapour. Fig. 5 was drawn to find the leak coefficient λ. It also illustrates the accuracy of the volume-calibration, when we remember that the whole of the vertical height of the diagram is only 20 parts in a total of 1,000.

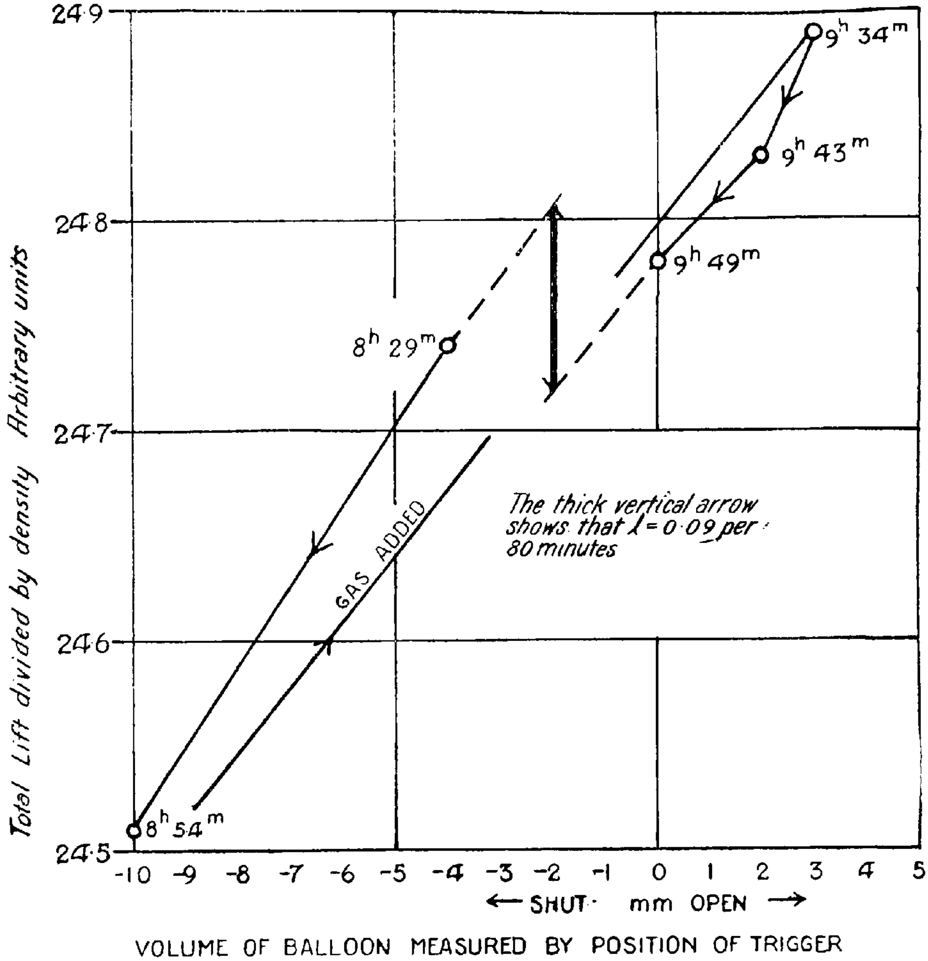

FIG. 5. Change in Composition of Gas.

Calibration Indoors.

Time, G.M.T.	Barometer at station mb. level. mb.	Assmann Thermometers. a. Dry.	Wet.	Total lift. Q g.	Trigger open by. mm.	Δp. mb.	Vapour pressure. mb.	Air density × const. millibars per degree abs.	$\frac{Q}{\rho^c}$ Total lift ÷ density × const.
h. m.									
8 22	1006·9	283·1	280·1	—	—	—	8·1	3·546	—
29	1006·9	284·2	280·8	87·37	− 4	—	8·4	3·532	24·74
53	1007·0	—	—	—	—	—	—	—	—
54	1007·0	283·8	280·2	86·72	−10	—	7·7	3·538	24·51
					− 10	8·3	—	—	—
	Some hydrogen introduced.								
9 30	1006·8	—	—	—	—	—	—	—	—
34	1006·8	284·4	280·6	87·86	3	—	7·9	3·530	24·89
43	—	285·0	281·3	87·44	2	—	8·6	3·521	24·83
47	1006·7	—	—	—	—	—	—	—	—
49	1006·7	284·7	281·0	87·34	0	—	8·3	3·525	24·78
54	—	—	—	—	1	11·5	—	—	—
	Some hydrogen let out.			82·32	—	5·9	—	—	—
	,,	,,	put in.	84·72	—	7·7	—	—	—
10 11	1006·8	—	—	—	—	—	—	—	—
14	—	285·0	281·1	82·62	—	—	8·2	3·522	23·46
29	1006·8	—	—	—	—	—	—	—	—
30	1006·8	285·0	281·1	82·02	—	—	8·2	3·522	23·29

From the table and diagram we deduce, in the notation of §3, $\lambda = 0{\cdot}09$ in 80 minutes. This measures the change in the composition of the gas. Then from (3·4) the ratio of the volumes $\frac{v_T}{v_R} = 1{\cdot}055_0$ at 10h. 14m. and $1{\cdot}062_0$ at 10h. 30m. Extrapolating to the time when the tail dropped off, $\frac{v_T}{v_R} + \zeta = 1{\cdot}067_7$. Pressure due to rubber when "ready," (Δp), by interpolation = 5·6 mb.

Then, for insertion in (5·4)

$$\left(\frac{v_T}{v_R} + \zeta\right) \frac{\theta_R}{(p + \Delta p)_R} = \frac{1{\cdot}067_7 + 285{\cdot}0}{1012{\cdot}4} = 0{\cdot}3006 = \left(\frac{\theta + \Delta\theta}{p + \Delta p}\right)_i$$

Theodolite Observations.—The balloon ascended point upwards. Eyepiece scale 5,400 units to 1 radian. Length of tail from centre of balloon to middle of pendant 10·35m.

Time. G.M.T.	Azimuth north = 0° east = 90°.	Elevation.	Tail on eyepiece. Scale units.	Radiation on balloon.	Computed height above theodolite metres.
h. m.					
10 37	74	5·6	53	Shade	102
38	73	6·1	35		169
39	72	7·2	24·5		284
40	—	8·0	20		385
41	71	8·5	15·8	Sun, but not the brightest.	517
42	71	8·6	14		590
43	70·2	8·2	11·4		692

At 10h. 43m. 23s. the observer remarked that the tail was falling. The release of the tail was clearly perceived as a rapid separation of the parachute from the balloon. Allow 3 sec. for personal equation and call the time 43m. 20s.

Height at this time extrapolated as 725m. above theodolite.

Height of theodolite above M.S.L. = 58m.

Height of balloon above M.S.L. =783m.

The estimated height of the occurrence appears to be definite to about 10 metres. The rate of ascent was 98 m/min. According to the formula of J. S. Dines it would have been 94 m/min. if the constant in the formula is taken at 84. (Cave & Dines.)

Next we require the correcting factor.

$$\left(\frac{1 + \Delta p/p}{1 + \Delta\theta/\theta}\right)$$

Δp_1 exceeds Δp_T by an amount depending on the temperature coefficient of elasticity of the rubber and estimated from §6 as 0·4 mb, so that $\Delta p_i = 11{\cdot}9$ mb, p_i is estimated as 940 mb.

So $(1 + \Delta p/p) = 1{\cdot}0126$.

Next to find $\Delta\theta_i$. It consists of two parts due severally to lag and to radiation. Take the lag first. Assuming an adiabatic lapse-rate (as there were many detached cumuli) and knowing the rate of ascent, we find as in §8

$$T\frac{d\theta_m}{dt} = 0{\cdot}4a$$

As only half the thermal capacity is effective, we may cut this down to 0·2a.

It remains to find the correction for radiation. The observer at the telescope reported the balloon to be in sunshine during the last three minutes of the ascent, but probably not in fully bright sunshine. Immediately after the ascent the readings of the following instruments were compared: the black bulb of §7, an Assmann aspirated thermometer, and a Dines air speed meter. This collection of observations indicated that, at an air speed of 60 m/min., the aforesaid black bulb was 6·6a hotter than the air in nearly fully bright sunshine, or 3·6a when the sun was obscured by cloud. Taking the excess of temperature as inversely proportional to the square root of the product of velocity and density* we find at the ascensional velocity of 94 m/min., and at a density of 6 per cent. less than at the surface,

Excess = 5·3a if sun dimmed by thin cirrus.
or ,, = 3·2a if sun obscured by cumulus.

An intermediate value of 4·7a was assumed. Guided by §7 we take for the red balloon 0·8 of this, that is 3·8a. Adding 0·2a for the lag we get $\Delta\theta_i = 4{\cdot}0a$. Assume $\theta_i = 280a$
Then

$$\left(1 + \frac{\Delta\theta}{\theta}\right)_i = 1 + \frac{4{\cdot}0}{280} = 1{\cdot}0143$$

Finally, at the point where the tail dropped,

$$\frac{\theta'}{p} = \frac{1 + \Delta p/p}{1 + \Delta\theta/\theta} \cdot \frac{\theta + \Delta\theta}{p + \Delta p}$$

$$= \frac{1{\cdot}0126}{1{\cdot}0143} \times 0{\cdot}3006$$

$$= 0{\cdot}3001 = \frac{1}{3{\cdot}332}$$

at a height of 783 metres above M.S.L.

Mr. W. H. Dines, before learning the above value of θ/p, kindly made an estimate of it, as far as could be done without measurement. From the screen temperature of 285·8a and from the date, the time of day, and the appearance of the sky—many detached cumuli—he estimated the temperature at 725 metres above the screen to be 279·6a. The mean temperature of the column of air up to this height was, therefore, 282·7a. And hence the pressure at the point where the tail dropped off was p_i, given by $\log_{10}1006{\cdot}8 - \log_{10}p_i = 14{\cdot}837 \times {\cdot}725 \times 282{\cdot}7$, so that $p_i = 922{\cdot}3$ mb. Hence

$$\frac{p}{\theta} = \frac{922{\cdot}3}{279{\cdot}6} = 3{\cdot}299 \text{ by estimate}$$

* *Vide* L. V. King. "Phil. Trans." A, vol. 214 (1914), pp. 373-432. Also L. F. Richardson, Proc. Phys. Soc., London. August, 1920.

Compare 3·332 by the lizard balloon, indicating a lapse rate more nearly adiabatic than had been anticipated.

Aeroplanes on this day found a lapse rate of about 7·5d per kilometre at places about 60k. from Benson. (*See* Daily Weather Report.)

§13. Use at Sea.

There is some hope that the apparatus might be workable at sea. The velocity of the ship does not enter into the calculations, and azimuths are not required. The elevation and the apparent length of the tail could perhaps be observed with sextants. The accuracy of weighing at sea was tested on s.s. Jupiter, between Newcastle and Bergen. The balance selected was of the slender portable type used by druggists. It was found to be easy to weigh 50g to 0·02g— which is an accuracy greater than we need—provided that the beam of the balance was placed along, not across, the ship. The degree of disturbance at the time may be estimated from the fact that some 10 per cent of the passengers were absent from meals.

§14. Conclusion.

A workable apparatus has been made. All of the measurements have been carried out with an accuracy of about 1 in 1000 of p/θ, with the exception of the correction for sunshine and possibly that for humidity. Even the former might attain the same accuracy, if the sky were uniform—either uniformly clear or uniformly overcast. On a day with detached cumulus the correction is apt to introduce an uncertainty of 5 in 1000 of p/θ.

The size of balloon required will depend on the height which it is desired to attain. A balloon having a nominal maximum circumference of 90 inches (=228 cm) did well for a height of 800 metres. The cost of such a balloon with case, trigger and tail, is about 8s. For greater heights either the balloon must be larger or the case made of some lighter material; otherwise it will not rise sufficiently quickly.

The presence of "recoveries of temperature" does not prevent measurements being made at any height.

If lizard balloons were regularly flown at a network of stations so as to give the density of the air at 0·5 k., it would, in clear weather be possible to draw the isobaric map at the 1k. level without waiting for the finding of registering balloons. These experiments were carried out at Benson. Mr. W. H. Dines was consulted at many stages, and encouraged me to proceed Some of the theodolite observations were taken by Mr. H. W. Baker and Mr. B. C Lewis. I had much help from two schoolboy visitors, C. Rowling and J. A. Gaunt. Mrs. Richardson made the chiffon cases. Professor A. J. Turner has contributed a report on the chiffon. Dr. P. C Austin and Dr. W Garnett kindly examined the proofs.