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CRACKER BALLOONS

FOR SIGNALLING

TEMPERATURE.

BY

Lewis F. Richardson, F. Inst. P.

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CRACKER BALLOONS FOR SIGNALLING TEMPERATURE.

By Lewis F. Richardson.

1. General description.

A balloon lifts a thermometer capable of closing an electric circuit when the temperature falls to a pre-arranged value. Then the electric current heats a fine wire, which ignites a charge of explosive. The explosion is seen through a theodolite, and the corresponding height is deduced from previous eyepiece readings on the tail.

The attraction of the method is its precision. It is possible to calibrate the thermometers to 0·1a and their lag, which can be roughly allowed for, is only about 0·6a. The uncertainty of the height, as measured by tail observations, may amount to 30 metres at 1 k., but even with an adiabatic lapse rate, 30 metres of height only corresponds to 0·3a. A disadvantage is that the apparatus has many parts and a corresponding number of possible ways of going wrong. It could be adapted to deal with recoveries of temperature above the starting point by arranging a thermometer to make contact as the temperature rose instead of fell. The weight of the apparatus to give two temperatures has been about 200 grammes, not including the balloon. A label is attached explaining how to dispose of a charge which should chance to reach the ground, without having burst.

The possibility of hearing the burst even above clouds is discussed in § 17.

This research was carried out at Benson Observatory with the facilities provided partly by Mr. W. H. Dines and partly by the Meteorological Office, especially the Instruments Division. The contact thermometers and the wind-channel were carefully constructed by Mr. H. W. Baker, who improved the design of several details as they passed through his hands. Mr. Baker and Mr. B. C. Lewis took some of the theodolite observations. The latter also made the igniters, crackers, and various fittings. Throughout I had the benefit of Mr. W. H. Dines' long experience of the upper air and of instrument design.

2. Figure of merit for comparing types of thermometers.

Shall we use liquid-in-glass, Bourdon, bimetallic, or gas thermometers? The following figure of merit, which was suggested by that in use for galvanometers,* helps to contrast these types. But it must not be followed blindly.

* *Vide* the Cambridge and Paul Instrument Co.'s catalogue.

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A good thermometer for the present purpose should, among other qualities :—

(i) Oppose a stiff resistance to fortuitous mechanical disturbance.
(ii) Have a widely open scale.
(iii) Have a very small lag.

These good qualities are to some extent mutually incompatible, so that we must form some sort of compromise or figure of merit depending on them all.

Let s be the displacement of the index.

F ,, ,, external applied force acting on the index.
θ ,, ,, temperature.
Q ,, ,, quantity of heat absorbed.

Let suffices denote the variables which are constant during the following differentiations.

Then $\left(\frac{\partial F}{\partial s}\right)_{\theta \text{ or } Q}$ measures the stiffness of the indicator.

$(\partial s/\partial\theta)_F$ measures the openness of the scale.

$(\partial\theta/\partial Q)_F$ is some rough indication of the rapidity of adjustment.

An exact treatment of the lag would be very complicated, involving the shape of the thermometer and internal and external conductivities. Let us be content with $\partial\theta/\partial Q$. Now the product of the three good qualities

$$\left(\frac{\partial F}{\partial s}\right)_{\theta \text{ or } Q} \times \left(\frac{\partial s}{\partial \theta}\right)_F \times \left(\frac{\partial \theta}{\partial Q}\right)_F$$

suggests itself as a measure of general excellence. But it will be observed that in the bimetallic type, for instance, if by the use of levers we increase $(\partial s/\partial\theta)_F$ in any ratio, then $(\partial F/\partial s)_{\theta \text{ or } Q}$ becomes decreased in the *square* of that ratio, while $(\partial\theta/\partial Q)_F$ does not change. Thus if we want a figure of merit which shall be independent of the presence of levers, we must square the factors $\partial s/\partial\theta$ and put

$$M = \text{Figure of merit} = \left(\frac{\partial F}{\partial s}\right)_{\theta \text{ or } Q} \times \left(\frac{\partial s}{\partial \theta}\right)_F^2 \times \left(\frac{\partial \theta}{\partial Q}\right)_F \qquad (1)$$

It will also be found that M is independent of the sizes of the stem and bulb of a liquid-in-glass thermometer, but characterizes the particular kind of liquid and of glass.

Many experiments were made with temperature indicators depending on the freezing of a liquid. For these the form of M in (1) is indeterminate because, if the freezing point is sharp, $(\partial\theta/\partial Q)_F = 0$ while $(\partial s/\partial\theta)_F = \infty$. However, as both differential co-efficients are made at $F = \text{const}$, we may cancel $\partial\theta$ obtaining for M the more convenient form

$$M = \left(\frac{\partial F}{\partial s}\right)_{\theta \text{ or } Q} \times \left(\frac{\partial s}{\partial \theta}\right)_F \times \left(\frac{\partial s}{\partial Q}\right)_F$$

Here follow data for M partly observed, partly calculated :—

		$\times 10^{-7} \times$ (degree C.)$^{-1}$
Bimetallic Spiral (Short & Mason thermograph) ...		1·4
Dines kite thermograph, small model		15
Dines balloon thermograph (bimetallic)		25
Flat helical copper tube filled with alcohol (H. W. Baker)		31
Bourdon thermograph by Camb. Inst. Co.		100
Air at N.T.P. neglecting heat absorbed by vessel ...		1,040
Mercury	In ideal glass bulbs of fixed size and negligible thermal capacity.	4,650
Paraffin Oil ...		7,500
Ethyl Alcohol ...		8,400
Chloroform ...		110,000
Freezing water, neglecting heat absorbed by vessel. When pressure exerted by the vessel at complete freezing has the following values in atmospheres :—		
	1,000 ...	14,000
	100 ...	630,000
	0 ...	infinite

The large values of M for freezing indicators, and the expectation that they could be relied upon without calibration, led to much attention being devoted to that type. But all attempts to overcome superfusion have so far been inadequate. In view of this failure, attention was directed to the liquid in glass type, which has the next highest figure of merit.

3. The balance of advantages.

The aim has been to make the cost of an ascent a general minimum with respect to all possible variations of parts of the apparatus. Only experience can decide how near we have come towards the general minimum of cost, but in seeking that low level we have certainly descended many slopes. Cost and weight are here closely connected, as the price of balloons increases rapidly with their size. The cracker, cell, contact thermometer and balloon have been chosen or designed so as to work together, and rather small variations in any one of them have been known to make the whole outfit unworkable when we employed only one cell, as formerly. For this reason full details have been given of the important particulars, although nowadays with four cells there is much greater latitude. There is a limit to the fineness of the wire which can be used for the igniter. This demands a certain current, which in turn settles the size of the electric cell and the permissible resistance of the contact thermometer. The contact thermometer must have a certain range of temperature, say, 30a, in which it can be safely stored. It is spoilt if heated or cooled beyond this range. Then it must have a certain sensitivity, say 0·1a. The safe range and the sensitivity together settle the length of the stem. Then the bore of the stem is controlled by the effects of the electric resistance of the column of mercury. The bore and the

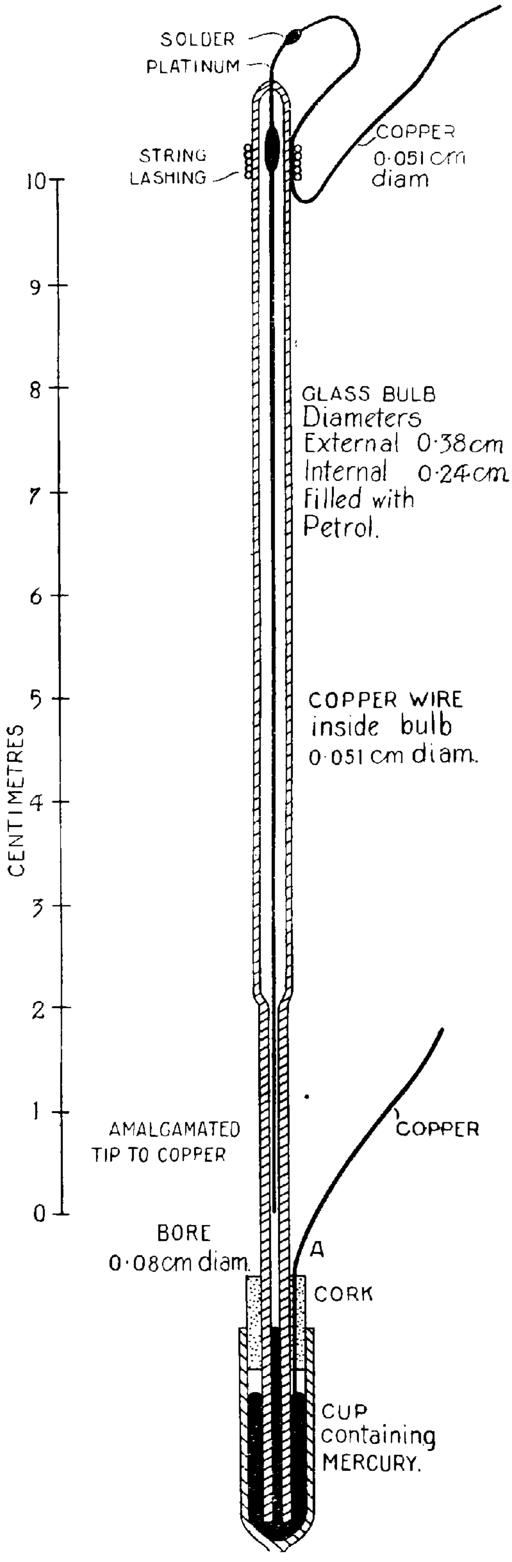

Fig. 1.—Section of Contact Thermometer Nos. 5, 6, 7 and 8. Scale value 0·1 cm/°C. Safe range 30a. The range might be increased by blowing a bulb near A.

sensitivity together define the volume of the bulb, which we are anxious to make small in order to reduce the lag. If a small additional bulb be blown on the stem the conditions are less stringent.

4. The contact thermometer.

This is shown in the drawing on which are given dimensions of one of our best specimens. As the bulb cools the mercury column rises until it makes contact with the copper wire. If cooled further until the mercury enters the bulb, the thermometer is spoilt, for the mercury does not completely retreat on warming. If overheated, petrol escapes and does not return. Consequently we protect these thermometers from changes by storing them in a cellar, a very small cellar made of two drain pipes sunk in the earth will hold a considerable stock. A thermos flask full of petrol would serve instead.

Some of the attempts which failed may be of interest. A platinite (=nickel steel) wire was tried in place of the copper inside the bulb, but it sometimes had a contact resistance of 10,000 ohms. even when apparently bathed by mercury, the reason being that a thin film of the insulating liquid—" methylated " ethyl alcohol, chloroform, or paraffin oil—remained between the wire and the mercury. This trouble does not occur with amalgamated copper. A bulb filled with chloroform gave a small lag, but the chloroform apparently reacted chemically with the mercury.

The contact thermometer might perhaps be improved by using a stem of smaller bore having a bulb blown on it below the end of the copper wire. That would increase the safe range and allow the bulb to be made smaller without increasing the electric resistance of the mercury in the stem.

Filling and adjusting the thermometers.—The glass tubes are placed with their open ends up in a tall jar containing the petroleum spirit. The jar is placed under the receiver of an air pump. By alternately pumping out the air and letting it in again, the tubes are filled. The jar is then inverted into a basin so as to turn the open ends of the thermometers downwards and to bring them below the liquid. The little cups containing mercury are then slipped on and held in place by corks. The adjustment is made at any later time by lowering the thermometer into petrol warmed to a suitable temperature, and giving the mercury cup a tap. Some of the liquid then escapes from the thermometer and its return is prevented by the mercury, which acts as a valve. The lower wires are not put in until needed, lest they contaminate the mercury.

At one time we were troubled by a black deposit forming on the surface of the mercury in contact with petrol in the stem. This made the contact temperature uncertain by as much as 1a. The deposit was suspected to be sulphide of copper, or of mercury, produced by sulphur in the petrol and copper from the wire, and two steps were taken to get rid of it:—(1) A purified petroleum spirit was obtained from Messrs. Madderton Loughton, Essex, and was subsequently stored in a glass bottle containing copper and mercury in contact with one another. (2) In filling the thermometers the petrol was kept out of contact with indiarubber as far as possible. These two steps partly succeeded, but there still remains some mystery.

Standardising the contact thermometer.—This is done in petrol, which is vigorously stirred all the time. Care must be taken not to cool the contact thermometer too much, as mercury which has once entered the bulb stays there, it is convenient, therefore, to be able to stop the cooling at any instant. This is arranged by having two vessels: a small one containing the thermometer for test, a standard spirit thermometer and a stirrer, and a larger reservoir of cold liquid into which the smaller vessel can be dipped as required. The contact thermometer is connected to an electric cell and a simple current-indicator. By means of judicious dipping, the cooling can be made fast up to the critical temperature, and then can be slowed down to permit exact measurement. The smaller vessel was a glass tube of about 3 cm. diameter, sealed at the lower end and divided into two compartments by a lengthways strip of vulcanised fibre. The compartments communicated at top and bottom. In one compartment a D-shaped cork plunger was worked up and down so as to give a lively motion to the petrol surrounding the thermometers in the other compartment. When the mercury looks bright, the temperature of " make " for slow cooling agrees with that of " break " for slow warming, to 0·1a.

In the course of months there may be a slow rise of contact temperature. Here, for instance, are successive standardisations of a good specimen of contact thermometer:—

No. 5, filled with petrol.

1919. Dec. 3.	1919. Dec. 13.	1920. Jan 14.	1920. Feb. 12.	1920. May 4.	1920. June 3.
a 264.5	a 264·2	a 264·7	a 264·8	a 265·3	a 265·2

This thermometer was kept underground meanwhile, with the lower wire in place. The electric resistance fell suddenly at contact from a large value to 0·165 ohm. The suddenness of the contact is, I think, due to the surface tension of the mercury. This is an advantage, as the full current is put through the igniter before the cell becomes in the least exhausted.

5. The time-lag of the contact thermometer.

The lag of the indication of the contact thermometer, behind the changing temperature of the air, is small but not negligible. When the thermometer is exposed to a current of air of constant temperature and of the same speed as that produced by the ascent of the balloon, the distance of the index from its ultimate position is reduced in the ratio $e = 2{\cdot}718$ in a time T, which will be called the "cooling time" and which has a value round about 40 secs. For fuller particulars see the table on page 104.

If θ_m be the temperature indicated by the thermometer, and if θ is the changing temperature of the air in which it is bathed during an ascent, then the equation governing the change of θ_m will be, when t is the time,

$$\theta - \theta_m = T \frac{\partial \theta_m}{\partial t}$$

That is to say, if $\partial\theta / \partial t$ is constant, the correction is the fall of temperature in a time equal to the "cooling time."

Now we have some idea of $\partial\theta_m/\partial t$, for at the start θ_m was equal, let us suppose, to the screen temperature at the ground; while, after a time which we observe, θ_m became equal to the contact temperature and the cracker burst. So, assuming a uniform change of temperature with time, we have $\partial\theta_m/\partial t$, and thence the required correction $(\theta - \theta_m)$. To apply these principles to the ascent of 1920, January 2nd, we have

screen temperature at ground	278a
contact temperature	269·2a
duration of ascent	790 seconds.

whence mean $\partial\theta_m/\partial t = 0{\cdot}011°$ per second. But for the thermometer used $T = 36$ seconds, allowing for air density and speed. And so the correction $(\theta - \theta_m) = 0{\cdot}4$a.

If several crackers were used on the same balloon, $\partial\theta_m/\partial t$ could be obtained more correctly. Or the known mean lapse rate might be utilised.

Laboratory determination of the cooling time.—The cooling of a warm body by a current of air presents a complicated problem, which has been attacked by many investigators and has been cleared up in part but not completely. That being so, we should if possible test the thermometers under exactly the conditions which they will meet in the ascent. This has been done in so far as they have been tested in a current of air which is vertical and which has a downward speed nearly equal to the upward speed of the balloon. A small wind-channel was constructed for this purpose.

Cooling time is defined as "the time for distance of index from its ultimate position to be reduced in the ratio $1:e$ where $e=2{\cdot}718$."

Number of contact thermometer.	Mean length of bulb in cm.	External diameter of bulb in cm.	Internal diameter of bulb in cm.	Kind of glass.	Nature of contents.	Excess of mean temp. above final temp.	Air Velocity.	Air density.	Position.	Cooling time.
						a	m/s.	g./cm.$^{-3}$ ×10^{-3}.		secs.
1	6·5	0·55	0·45	soda	paraffin oil	1·5	1·5	1·23	Z	47*
3	4·7	0·56	0·45	soda	chloroform	1·5	1·5	1·23	Z	35*
1	6·5	0·55	0·45	soda	paraffin oil	2	1·7	1·23	X	53
3A	4·7	0·56	0·45	soda	petrol ...	—	2·8	1·24	X	—
5	8·4	0·38	0·24	soda	petrol .	c. 2	2·8	1·24	X	31
"	"	"	"	"	" ...	"	"	"	Y	32
9	9·1	0·41	0·30	soda	petrol .	1·2	2·8	1·24	X	42
"	"	"	"	"	" ...	2·2	"	"	X	35
12	9·3	0·41	0·30	soda	petrol ...	14 to 0·3	0	1·22	X	123

* Out of doors.

Positions :—

X. Tube vertical parallel to downward current, if any.

Y. Tube slightly inclined so that area of projection of bulb on plane perpendicular to vertical current is increased 3-fold.

Z. Tube vertical, relative velocity horizontal.

Balloons rise at various speeds V through air at varying density ρ. But experiments on cooling of wires by L. V. King* taken in conjunction with Leonard Hill's† observations on his kata-thermometer indicate that when other things are the same, we shall probably have

$$\text{"cooling-time"} = \frac{1}{A + B\sqrt{V\rho}}$$

where A and B are constants, at least approximately. They may be estimated from the data in the preceding table relating to the closely similar thermometers Nos. 9 and 12. Take the cooling time as 123 secs. when $V=0$, then $A=1/123$. Also the cooling time for small differences of temperature, is 42 secs. when $V\rho = 280 \times 124 \times 10^{-3}$ c.g.s. units. Thus in C.G.S. units

$$A=0{\cdot}0081 \quad , \quad B=0{\cdot}0266$$

for thermometers like Nos. 9 and 12 in the table.

The experiments of Dulong and Petit, lead us to expect‡ that A is proportional to $(\theta_m-\theta)^{+0{\cdot}23}\,p^{-0{\cdot}45}$; but for present purposes it may be taken as roughly constant, as it only effects a small correction, and as observers are not unanimous in the type of formula which they support.

* "Phil Trans." A Vol. 214 (1914) pp. 373—432.

† Q.J.R. Met. Soc. July, 1919.

‡ *See* L. F. Richardson, "*Convective Cooling and the Theory of Dimensions.*" Proc. Phys. Soc. London, 1920.

6. The igniter.

A piece of Eureka wire of No. 47 S.W.G. (0·051 mm. diameter) is wrapped in gun cotton. This bursts into flame when $\frac{3}{4}$ ampère is passed through the wire. To obtain this current from a 1·4 volt cell, the wire must be very short. A length of 0·25 cm. has been used. It is soldered to copper leads of No. 25 S.W.G. (0·51 mm. diameter). To make igniters, the insulated copper wire is cut off in lengths of 40 cms. Each length is doubled, and the two strands twisted together. The loop is then cut open; the ends are hammered flat, scoured with emery, and hooked over. The bare eureka wire is engaged with

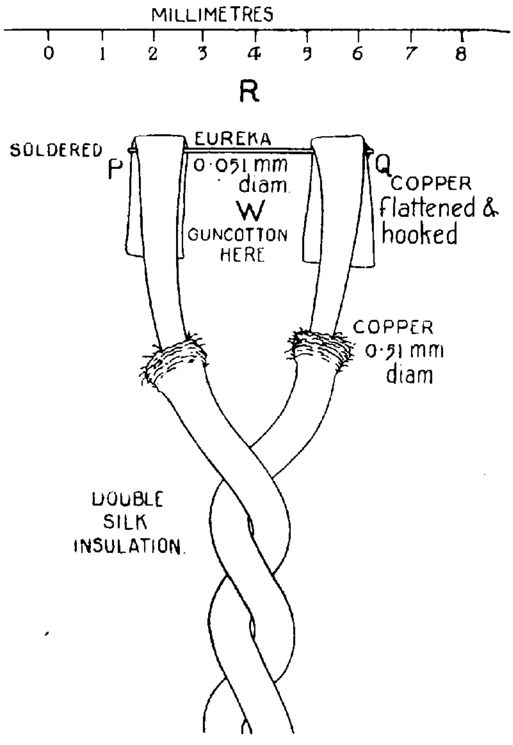

FIG. 2.—An Igniter for a Cracker.

the copper hooks, as shown in the sketch. The hooks are then nipped tight, and a soldering bit is brought to their *outer* sides at P and Q. After soldering the flux is removed by dabbling the ends in a suitable liquid. They are then dried. A wisp of gun cotton is inserted through the opening *w*, and its two ends are twisted together at R. The resistance of the finished igniter is 0·5 ohm. As it is possible that the delicate eureka wire may be broken while being inserted in the cracker, it is best to test the resistance in the finished cracker. This may be done quite safely by using a Wheatstone bridge and a current of 1/100 ampère; but to guard against an accidental misconnection it is well to put the cracker outside the laboratory at the end of a long pair of leads. While crackers are in stock the outer ends of the leads are twisted together so that chance contact with a source of E.M.F. would not cause an explosion.

7. The cracker.

The cracker was made, like a firework, of strong paper, glued and rolled up to form a tube. The ends were constricted with string. When the glue was dry, one end of the tube was plugged with plaster of Paris. Some black gunpowder was poured in. Then came the igniter well wrapped in dry guncotton, then more black powder, finally a stopper of plaster round the emerging wires. The dimensions of the cracker were :—length 10 cms., outer diameter 1·3 cms., mass-complete 16 grams. For night work magnesium powder could be introduced.

8. The intermediate popguns.

Where more than one thermometer is connected to the same battery of cells, only the explosive which goes off last can be allowed to burst the balloon. The others must satisfy the following requirements :—(1) they must give a visible signal; (2) the explosion must break the circuit, so as to prevent the cell from becoming exhausted; (3) it must not injure the rest of the apparatus. The arrangement shown in Fig. 3 was used with success. It causes a sheet of white paper to drop off.

A very small charge, 0·35 g., of gun cotton is fired within a cardboard tube. One end of the tube is securely closed by plaster of Paris. The other end is stopped by a cork to which a piece of white paper is pinned. The cork is blown out and falls with the paper. That is the signal. Between the cork and the guncotton is a small metal disc. That is blown out also, separately from the cork, and drags with it one of the electric wires. The other wire is held by the plaster and, for security, is tied to the cardboard tube outside. Thus the electric circuit is broken. The very delicate fuse wire could not be mounted, unless the copper leads, which it connects, were held steady relative to one another. So the copper wires are twisted round a splinter of bamboo. But the bamboo is shaved smooth and slightly tapering and one of the twists is made not too tight so that it can slip off, and is then secured with a trace of beeswax. To protect this slipping-joint from accident as it is being inserted into the cardboard tube, the wire above it is formed into a helical spring. The fuse wire is engaged in the copper hooks, which are then nipped tight and soldered. Care must be taken to see that the fuse is touching guncotton. It is necessary to measure the resistance of the finished popgun to make sure that the fuse wire has not been torn off while being inserted in the tube.

9. The cells.

The cells were obtained from the British Ever Ready Co., Hercules Place, Holloway, London, N.7., and are known by them

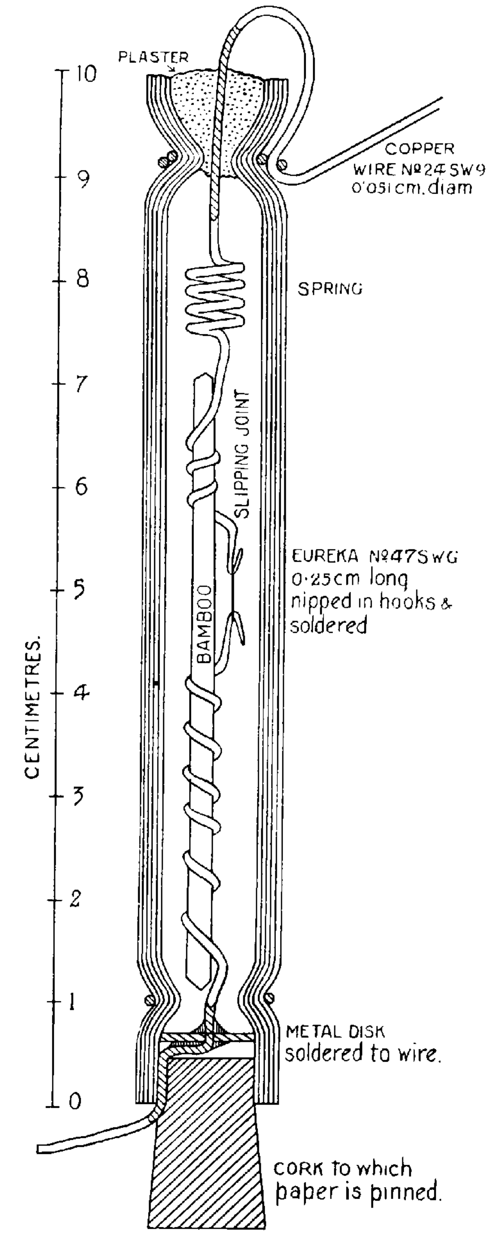

Fig. 3.—Intermediate Pop-gun. Partly in section. Guncotton not shewn.

as belonging to "battery pattern No. 214." They are paste Leclanché cells weighing 15 grammes each. A test of one in cooled petrol gave the following results :—

Temperature a.	281	269	254	230	217	216
Voltage on open circuit.	1·48	1·48	1·48	1·21	0·29	0·22

that the voltage would be satisfactory up to a height of four kilometres at least. The same cell was now short-circuited through 1·2 ohm. (which is roughly the resistance of cracker, thermometer and leads in series) the initial current was read after a few seconds and then immediately cut off.

Temp. a.	247	253	256	258	261	264	268	280
Initial current ampères	0.02	0·11	0·27	0·44	0·48	0·51	0·51	0·57

So the current falls off at temperatures at which the voltage is still high. The voltage at 280, which came last in order of time, was now only 1·33. The above-mentioned cell had been in stock for five months.

A fresh cell, tested the day after it was received from the makers, gave the following result :—

Temp.	Voltage on open circuit.	Current through 1·1 ohms after 10 sec.
a 290	Volts. 1·52 before.	Ampères. 0·72
260 260·5	1.44 before 1·37 after (rising.)	0.54 —
245 „	1·38 before. 1·28 after.	0.16

The current was left on for 10 seconds only at each temperature, as this would be more than time enough to burst a cracker.

Altogether the cells may be taken as good down to 260a.

10. The parachute.

This is a piece of thin cotton fabric, known as nainsook, 50 cm. square. It serves three purposes :—To prevent the falling cell from injuring anybody, to prevent the balloon capsizing during the ascent, and as a tail for the measurement of height by the eyepiece micrometer.

On one occasion a balloon was seen to burst at a height of 7,900 metres. There was no smoke puff and we concluded that the cracker had failed to act. The apparatus reversed, the rags of the balloon being below, the parachute above. It fell thus to a height of 6,450 metres in 4m.20s. Both heights were measured by the tail. That is a descending speed of 5·6 m/s. The parachute was nainsook, 50 cm. square when flat, and the load on it was 131g. plus the remains of a balloon initially weighing 53 g. In the denser air near the ground its speed might be expected to be only 4 m/s. This size of parachute has been considered to offer sufficient protection to the wayfaring man.

When two thermometers were sent up, a parachute measuring 65 × 65 sq.cm. was used. It was held open by a ring of aluminium wire. It weighed 27g.

11. The warning label.

The label is dipped in melted wax to protect it from the weather, it bears the following inscription :—

> INVESTIGATION OF THE UPPER AIR.
>
> CAUTION.
>
> ---
>
> **The white object marked explosive is an electric cracker intended to burst in the air. In case it has not yet exploded it may safely be got rid of by chopping it free with a spade and burying it, when it will rot harmlessly away.**

12. Assembling the parts.

Profiting by Mr. W H. Dines' experience of a wake of heated air left behind a sunlit balloon, the screen was at first fixed on the top of the balloon. The screen was a cylinder of aluminium foil provided with three wire legs. Its feet were attached to the inflated balloon by sticking pieces of tape across them. The adhesives used were seccotine or "styx." These appear to have no injurious action on indiarubber. To support the contact thermometer within the screen there was a wire ring at the lower end and an insulating crossbar of bamboo at the upper end. The leading wires were wrapped round the bamboo, which was prevented from falling out by a judicious use of sealing wax. The cell and cracker, which hung below the balloon, sufficed, when aided by the parachute, to prevent it capsizing.

The upper position of the screen requires that the balloon be inflated before the rest of the apparatus is assembled, but that is awkward, especially as the balloon is too big to go through an ordinary door.

A meteorological instrument should be as ready as a fire engine.* With readiness in view the arrangement was altered

---

* Mr. H. W. Baker's phrase.

to the form shown in Fig. 4. The radiation shield is below the balloon, but to one side of the wake. It is mounted on one end of a boom, and either another thermometer or else some of the cells form a counterpoise. The arrangement of cells, boom, shield and cracker can be prepared weeks beforehand, and the thermometer and balloon attached at the last moment. Very

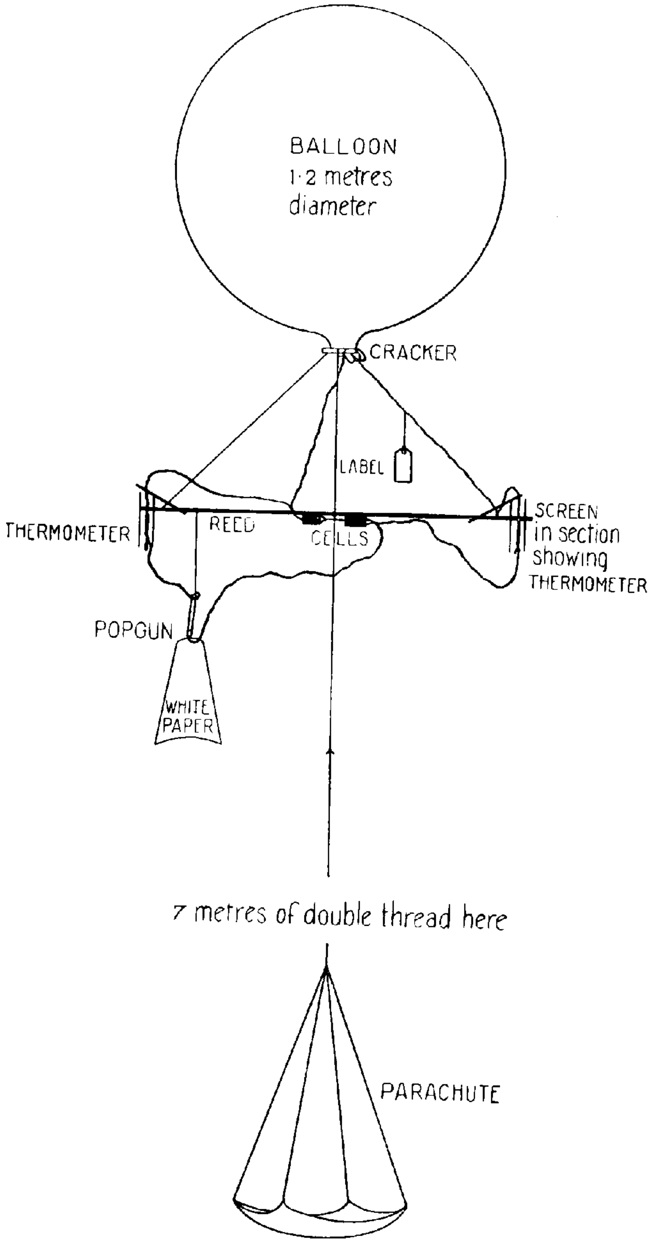

FIG. 4.—Outfit for two thermometers. Wire is represented by wavy lines, string by straight lines.

satisfactory booms are provided by a bamboo-like reed which grows beside the Thames. Dried hemlock is also very light and stiff.

Fig. 4 shows the arrangement for signalling two temperatures. For a single temperature both balloon and parachute are smaller.

13. Summary of electric data.

Resistances external to battery.		Ohm.
4 metres copper wire 0·51 mm. diam.		0·28
10 twist joints at 1/200 ohm each		0·05
Igniter 0·25 cm. Eureka 0·051 mm. diam. ...		0·50
Contact thermometer		
Mercury column 3 cm. long and ·005 sq. cm. cross section ...	0·057	
Platinum copper, etc., to total of		0·16
Total outside of battery		0·99

A cracker, tested with slowly increasing current, was not burst at 0·70 ampère, but went off at 0·75 amp. A single cell suddenly connected through an external resistance equal to the above total, might give this 0·75 amp. if very fresh, which explains early successful ascents, but if it were either stale or much cooled (*see* §9) it would just fail to give the necessary current, this explains, I think, several failures. At first we lacked an ammeter or voltmeter. We now use four cells connected in series-parallel. They should be ample

14. Masses and balloons to lift them.

Summary of masses for a single cracker.	Grammes.
Boom of hemlock or a bamboo-like plant 1·5 metres long	9
4 cells at 15 g. each...	60
Cracker	16
Aluminium radiation screen 0·012 cm. thick ...	14
Contact thermometer	9
Label	1
4 metres copper wire No. 24 S W G	9
10 metres thin twine	4
Parachute nainsook 50 × 50 cm.	15
Total in addition to the balloon ...	137

For two temperatures the mass was increased to a total of 196g. This is much less than double the amount for a single cracker because the same battery and boom serve for both. The parachute used with two crackers measured 65 × 65 sq. cm. For the amount of information obtained, it is more economical to use two than one thermometer per balloon.

Suitable balloons.—For a single cracker we want to lift an apparatus weighing 137 g. with a speed of say 130 metres per minute.

The Instruments Division of the Meteorological Office sought for balloons to satisfy this requirement and some of the results are given below.

A wide-necked rubber balloon weighing 53g. when empty and which comes from Canada has been used, but it only attained a speed of 103 metres/min.

On another occasion we used a balloon of this pattern, but rather smaller (46g. empty) in tandem with a paper balloon marked M.I.D. Imbercourt which was pearshaped and had a maximum horizontal diameter of 80 cm. The speed of this combination was observed to be 117 metres/min.

The largest size of pilot balloon, 150in. (=381 cm.) in nominal circumference lifted an outfit weighing 88g. with a speed of 134 metres/min. But that outfit had only one cell, which is not enough.

A rubber balloon weighing 450g. empty, of the type used with Dines meteorographs, lifted the two-temperature-outfit at a high speed giving a sufficient angular elevation but an unduly large lag. *See* p. 103. These balloons are costly. A doped paper balloon, if large enough, ought to serve for crackers, but so far we have not found one.

Strange to say the observed speed of ascent has commonly exceeded that deduced from the free and total lifts by the formula of J. S. Dines and the constant 84. L. H. G. Dines has also observed this with loaded balloons. It is surmised that the parachute and load, by preventing the balloon from rolling, prevent it from communicating so much momentum to the air.

15. An ascent with one thermometer.

Benson, 2nd January, 1920.

Observers : W.H.D., L.F.R., H.W.B., B.C.L.

Contact temperature 269·2a. Thermometer No. 8, similar to No. 5 described in § 5.

The radiation screen was mounted on the top of the balloon The cracker was tied against the neck of the balloon. A single cell was hung lower down so as to assist the parachute in keeping the screen uppermost. This arrangement has since been improved in the sense already explained. At 12h. 3m. G.M.T., $13\frac{1}{6}$ minutes after the start, the balloon suddenly disappeared in a cloud of smoke. The tail observations, when plotted out and fitted with a straight line, show that the height of the burst was 1,780 metres above the theodolite. The scatter of the individual height observations around the straight line was represented by a standard deviation of 39 metres. The ascensional velocity was 2·23 m/s.

The temperature in the Stevenson screen at the level of the theodolite was 278a. This occasion has already been used as an example in § 5. The correction for lag comes to 0·4a and the corrected temperature to 268·8a. The mean lapse-rate was thus 5·2a per kilometre. The theodolite standing 58m above sea level, the temperature 268·8a corresponded to 1,838m above mean sea level.

According to the Daily Weather Report an aeroplane ascent at South Farnborough, 47 kilometres south-east and 2 hours previous showed a temperature of about 265·5a at 1,800m, which is 3·3a lower; the surface temperature was also lower at South Farnborough by about 3·5a, so that the mean lapse-rate was practically the same.

16. An ascent with two thermometers.

Benson, June 4, 1920.

Observers: RUSSELL MUNDAY; L.F.R.

The apparatus was that shown in Figs. 1, 2, 3 and 4.

The rubber balloon was of the size used to lift Dines meteorographs, but for economy's sake, a balloon was selected which was of suspect quality, having been in stock for two years. For crackers are not intended to reach the stratosphere. The balloon was inflated to a total lift of about 1,050 g. Empty it weighed 450 g. The attachments weighed 200 g. Thus according to the formula of J. S. Dines the ascensional velocity should have been

$$84 \times \frac{(1050 - 450 - 200)^{\frac{1}{2}}}{1000^{\frac{1}{3}}} \text{ m/min.}$$

= 168 metres/min. = 2·8 m/s. Actually it was more, as is usual for balloons with parachutes.

The contact-temperatures had been chosen to suit the previous evening which was warm and hazy, but the apparatus had not been sent up then, owing to the insufficient lift of a paper balloon. The evening of June 4 was colder, and by the time the balloon was tied to the cracker, and all ready to go, except for the last electric connection, it was found that the first thermometer was already making contact, indicating a temperature just below 283·5a. The chief object of this ascent being to test the working of the double outfit, it was judged best to warm up this thermometer with the finger. The last electric connection was then made, and the balloon released when the thermometer was about 3a off its contact. While the theodolite was being set on the balloon, a group of children whose assistance had not been welcomed, began to call out that a white paper was falling. This was the signal from the intermediate popgun. No pop was heard, and the rest of the apparatus, seen large through the telescope, appeared uninjured. So the explosion must have been a gentle one, as was intended. It occurred probably after rather less than a minute from the start. The following are the readings :—

Tail length 13·0 metres. Scale value of micrometer 5,400 units to one radian.

G.M.T.	Remarks.	Angular elevation	Eyepiece scale.	Computed height.	Azimuth of balloon.
19h.					
49m. ...	balloon released	—	—	0	—
49m. 50s.? ...	intermediate pop-gun.	—	—	—	—
51m. ...	—	22·3	56	440	—
52m. ...	—	20·4	41	560	—
52m. 35s. ...	cracker ...	19·1	—	720	south.

The height of 720 metres was obtained by plotting observed heights against times, and assuming a linear relationship. The ascensional velocity comes to 3·4 m/s. It would have been better to have observed the tail more frequently.

The explosion of the cracker was seen as a tawny flame surrounded by smoke, enveloping the whole balloon. A few seconds later a sound " omf " was heard, reminiscent of anti-aircraft shell, but much gentler. Mr. B. C. Lewis also saw and heard the burst without instruments from the other end of the village. This cracker was of the kind described on p. 106, weighing 16g. It was thus just audible at a sloping distance of 2·2 k., which is about what we should have expected from some previous observations made at 150 m. distance in comparison with the sound of a falling ball.

We have now to compute the lag according to the method of § 5. The first thermometer No. 12 having been warmed by hand 3·5a above the initial air temperature. cooled 3a in 50 seconds, which is, at least roughly, what we should expect. The second thermometer was No. 14, to which the constants A and B of §5 apply. The ascensional velocity V was 340 cm. sec. and the density ρ at the place where the cracker burst was probably $1{\cdot}15 \times 10^{-3}$ c.g.s. So $\sqrt{V\rho}=0{\cdot}63$ c.g.s. and the " cooling time " comes to 41 seconds. The thermometer cooled, from the surface temperature of 283·5a at the moment of release, in 215 seconds to its contact temperature of 278·6a. Thus the correction for lag

$$=41 \times \frac{(283{\cdot}5 - 278{\cdot}6)}{215} = 0{\cdot}93\text{a}.$$

We should have had a smaller correction if the balloon had not risen so fast.

The result is that the air temperature at a height of 720 metres above the theodolite (that is 778 above mean sea level) was $278{\cdot}6-0{\cdot}9=277{\cdot}7$a at 19h. 53m. At this time the temperature at head level, obtained from a thermograph, but checked by an aspirated thermometer was 283·0a. So the lapse rate was (283·0–277·7)/720 = 7·4a per kilometre. It was a clear evening, following a cool overcast day with wind from NNE.

A telegram containing the computed result was despatched 38 minutes after the balloon had burst, or 1 hour 40 minutes after the observers came on the scene.

The remains of this apparatus came to hand some months later. The balloon was in tatters, the boom was broken up, but the glasswork was uninjured. The slipping joint of the pop-gun had not slipped as much as it should have done, for the metal disc was still in the mouth of the paper tube, but the eureka had disappeared as if it had been melted.

17. The possibility of observing by sound in thick weather.

The original hope was to hear the explosion and to note its time of occurrence. That, together with a foreknown rate of ascent, would give the height. But the charges of powder, which we have used, have been only 10 g., and their explosion has only just been audible at a direct distance of 2·2 k, which is not enough. (*Vide* § 16.)

If more powerful crackers were employed, more precautions would be necessary to protect the finder of a cracker which had chanced to come to earth unexploded. A possible safety device would be a short-lived cell. But as the human ear is more sensitive to sounds, having a pitch near 600 vibrations per second than to those above or below, it may be that an explosion is an inefficient audible signal, and that we should attempt instead to make a whistle or siren blown by burning cordite.