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Aerological Sounding Balloons [1]

Gordon M. Martin, John Mandel, and Robert D. Stiehler

A low-temperature patch test for sounding balloons is described. In this test a circular piece is cut out of the rubber film, clamped around its circumference, and inflated until it bursts. Equations applying to the patch test and to the flight of sounding balloons are developed. The important properties in determining the flight elevation are found to be the flaccid length of the balloon and the elongation of the rubber film. The effective elongation is defined as the average elongation of the entire balloon film at the pressure at which the weakest part of the balloon will fail. A method of estimating this effective elongation from patch test data is given. Correlation was found between patch-test data and night-flight elevations. On the basis of flights made with thermistors both inside and outside the balloon, the temperature of the balloon film at burst is estimated to be 0 to 4 Celsius degrees colder than the surrounding air at night and 20 to 30 Celsius degrees warmer than the surrounding air in the daytime.

1. Introduction

Sounding balloons are used on routine weather flights to carry radiosondes into the stratosphere. In the United States the balloons are usually made of a neoprene film with an unstretched thickness of about 0.003 in. and weigh 500 to 600 g. They are inflated with helium or hydrogen to a specified lift and, when released, rise at a rate of about 0.3 km/min to elevations of 15 to 30 km before bursting. At these altitudes the temperature may be as low as −70° C and ozone, ultraviolet radiation, and cosmic radiations are much more prevalent than at the surface of the earth. At the request of the Department of the Navy, Bureau of Aeronautics, the National Bureau of Standards has been investigating the factors involved in the flight of sounding balloons. This paper outlines some of the results obtained.

Laboratory tests have been made on special balloons and on balloons from regular production lots. Other balloons from the same lots have been flown by the Weather Bureau. Some tests that have been made are: (1) conventional tensile tests of dumbbell specimens at room temperature and at −40° C, (2) balloon inflation tests, using air at room temperature, and (3) brittleness tests at −60° C. The results of these tests did not correlate with the flight elevations attained in service. Some of the factors contributing to this lack of correlation may be: (1) tensile tests on dumbbell specimens of thin films are extremely sensitive to small variations in the character and condition of the cutting die, (2) tests of the film at room temperature and even at −40° C are not indicative of the properties at the lower temperatures encountered in service, (3) brittleness tests involve the sudden bending of the specimen at low temperature, whereas in flight the film is stretched gradually at the same time it is being cooled, and (4) conventional tensile tests involve stretching the rubber in one direction, whereas during flight the film experiences a two-dimensional stretching. These considerations indicated the advisability of using a patch test at a temperature approximating that encountered in flight. Most of recent work at NBS has been concerned with such a test.

2. Patch Test

In the patch test a circular piece of the film, or patch, is clamped around its circumference and inflated until it bursts. The film passes through a series of forms approximated by a flat surface, a hemisphere, a sphere with a section cut off at the bottom, and finally an oblate spheroid. Diagrams of these forms are given by Treloar.[2] The greatest stretching takes place near the center of the patch, and the break usually occurs in this region. In this work the inflation is conducted inside a cold box maintained at the desired temperature by a detachable servo-unit that operates with dry ice. The patch is inflated with superdry nitrogen in order to introduce as little water vapor as possible into the cold chamber. The compressed nitrogen passes from its container through a two-stage pressure regulator, a needle valve, a flowmeter, and then into a large copper tube inside the cold box, where it cools down before coming into contact with the patch. Figure 1 shows the equipment, and figure 2 shows a patch during inflation.

The quantities measured are the differential pressure across the patch, the distance between bench marks on its surface, and the maximum dimension of the patch. A circle, 1 cm in diameter, is marked at the middle of the patch. During inflation the diameter of this circle is measured by a flexible scale that rests lightly on the patch and follows the shape of its upper surface. The scale is observed through a removable thermopane window in the top of the cold box. This measurement in centimeters is equal to the elongation [3] of the region near the center of the patch. The differential pressure across the patch is measured by a mercury manometer or by a bellows sensitive to pressure that is connected to an electric-

[1] This work was financed by the Department of Navy, Bureau of Aeronautics.

[2] L. R. G. Treloar, Strains in an inflated rubber shell and the mechanism of bursting, Trans, Inst. Rubber Ind. [6] **19,** 201 (London, April 1944).

[3] In this paper, elongation is defined as the ratio of stretched length to unstretched length and not as the percentage increase in length.

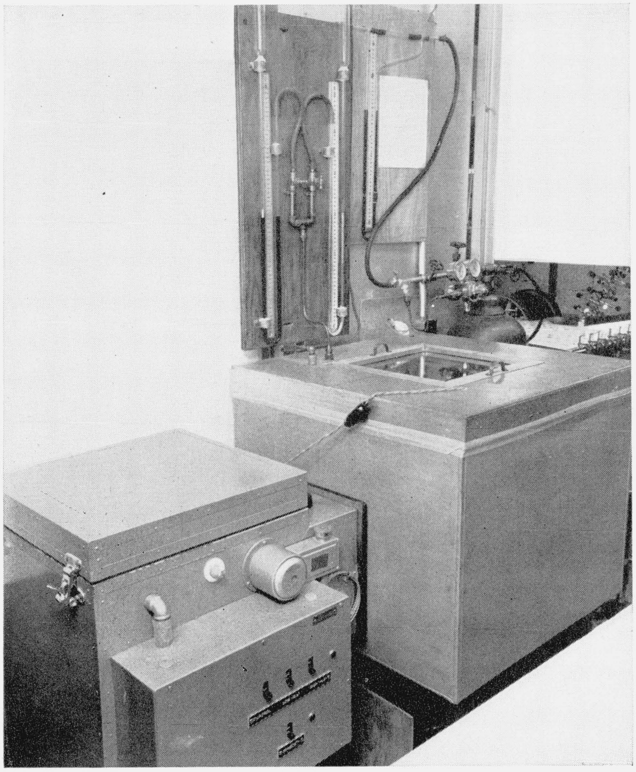

FIGURE 1. *Patch test equipment.*

The dry-ice chamber is on the left; the cold box containing the patch is on the right.

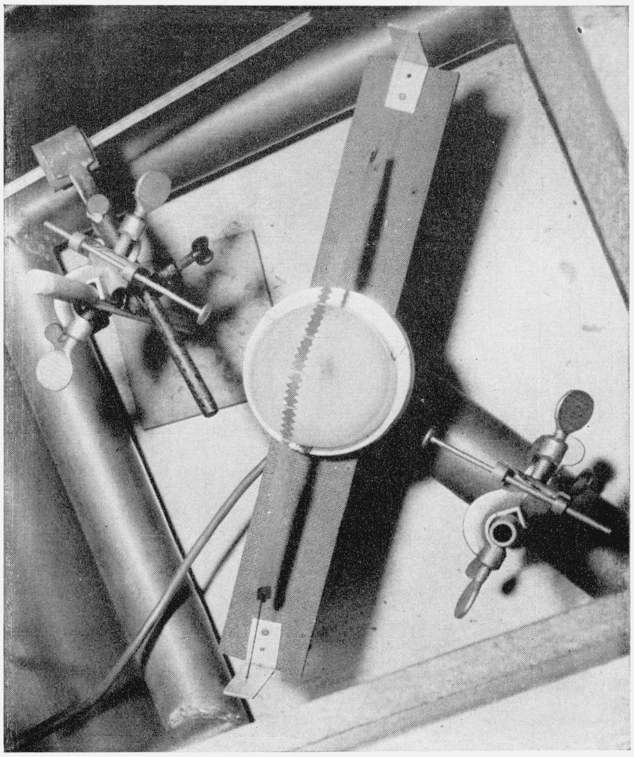

FIGURE 2. *Patch during inflation.*

The flexible scale for measuring elongation is resting on the patch, but the 1-cm circle is not visible in the photograph. The pistons for obtaining the major diameter and the large copper tube for cooling the inflating gas may also be seen.

measuring system. The major diameter at burst is measured by means of two freely moving pistons with flat heads, which are pushed outward by the expanding patch. The distance between the pistons is measured with a steel scale after the patch has burst.

Initial patch tests were made at several fixed temperatures. It was found that the ultimate elongation of the neoprene film decreased, and the stiffness and tensile strength increased as the temperature was lowered. As the temperature coefficients were different for different films, the properties at room temperature were not a good indication of the low-temperature characteristics of the rubber films.

The method finally developed for the patch tests involves a prestretching at a temperature higher than that at burst. This corresponds more closely to the way the film is stretched in flight. The patch inflation is started at $-40°$ C. The volume rate of inflation is held constant throughout the test. When the 1-cm-diameter circle reaches a diameter of 2.5 cm, the surrounding air is cooled until the temperature is reduced to $-60°$ C. The temperature is held at $-60°$ C until the patch bursts. Five to 10 min are required to cool the air from $-40°$ to $-60°$ C, and the entire test lasts 15 to 20 min. This test is referred to in this paper as the $-60°$ C patch test.

3. Equations Applicable to Patch Test

Approximate relations giving the tensile strength and elongation in a patch test have been derived by C. F. Flint and W. J. S. Naunton.[4] Their equations are

$$S_B = \frac{1.35PR_e^2}{at_0}, \quad (1)$$

$$E_B = \frac{2.60R_e}{a}. \quad (2)$$

S_B is the tensile stress at burst, based on the original cross section; P is the differential pressure across the patch; R_e is the equatorial radius of the patch at burst; a is the radius of the circular aperture, that is, half the inside diameter of the ring used to clamp the patch; t_0 is the thickness of the unstretched film; and E_B is the ultimate elongation or the ratio of the final to the initial length of a line drawn on the film.

Solving (2) for R_e and substituting in (1) gives

$$S_B = \frac{PE_B^2 a}{5t_0}. \quad (3)$$

[4] C. F. Flint and W. J. S. Naunton, Physical testing of latex films, Trans. Inst. Rubber Ind. **12**, 367 (London, 1936–37).

In the patch test used in this work, a is 1.25 in. Substituting this value into (2) and (3) gives

$$E_B = 2.08R_e = 1.04D_e, \qquad (2a)$$

with R_e and D_e in inches.

D_e is the equatorial diameter of the patch at burst.

$$S_B = \frac{PE_B^2}{4t_0}, \qquad (3a)$$

with t_0 in inches. S_B is in the same units as P.

As the diameter of the patch at burst was measured directly with pistons and the elongation was determined from measurements on a circle, 1 cm in diameter stamped in the middle of the patch, it was possible to determine the validity of eq (2a). According to this equation, $E_B/D_e = C$, where C is 1.04 in., with D_e in inches. Experimental values of C are: 0.97, 1.01, 0.93, 0.96, 0.98, 1.00, 1.00, 1.04, 1.00, and 1.08. Each of these 10 values represents the average for a number of patches from a particular balloon. The differences between these values and 1.04 may be the result of several causes. When the rubber film is near the glass-transition temperature, part of the film may freeze and the remainder continue to elongate, thus changing the value of C. Variations in the area of rubber exposed, because of wrinkles in the film or slippage in the clamp, would also affect the value of C. The value of C is probably slightly different at different temperatures and for different compounds.

A relation between the bursting pressure, P, in a patch test and the differential bursting pressure, P_d, across the surface of a uniform spherical balloon made of the same material is given in eq (10) below and can be derived as follows:

Imagine cutting the balloon along a great circle just before it bursts. The tensile strength, based on the final cross-sectional area, S'_B, may be found by equating the forces pushing the halves apart to the tensile forces holding them together.

$$\pi R_B^2 P_d = 2\pi R_B t_B S'_B \qquad (4)$$

or

$$S'_B = \frac{R_B P_d}{2t_B}, \qquad (4a)$$

where R_B is the radius of the balloon at burst, and t_B is the thickness of the rubber film at burst.

Now, since $R_B = E_B R_0 = (E_B D_0)/2$, where R_0 is the unstretched, or flaccid, radius of the balloon, and D_0 is the flaccid diameter,

$$S'_B = \frac{R_0 E_B P_d}{2t_B} = \frac{D_0 E_B P_d}{4t_B}. \qquad (5)$$

The tensile strength based on the original cross-sectional area, S_B, is found by equating the forces pushing the halves of the balloon apart to the tensile forces holding them together, expressed in terms of the unstretched cross-sectional area.

$$\pi R_B^2 P_d = 2\pi R_0 t_0 S_B \qquad (6)$$

$$S_B = \frac{R_B^2 P_d}{2R_0 t_0} \qquad (6a)$$

Letting $R_B = E_B R_0 = (E_B D_0)/2$ gives

$$S_B = \frac{R_0 E_B^2 P_d}{2t_0} = \frac{D_0 E_B^2 P_d}{4t_0} \qquad (7)$$

Combining eq (4) and (6) gives the relation between the tensile strengths based on the final and on the original cross-sectional areas.

$$S'_B = \frac{R_0 t_0 S_B}{R_B t_B} = \frac{t_0 S_B}{t_B E_B}. \qquad (8)$$

Assuming a constant volume of rubber (or constant density),

$$4\pi R_B^2 t_B = 4\pi R_0^2 t_0 \qquad (9)$$

or

$$\frac{t_0}{t_B} = \frac{R_B^2}{R_0^2} = E_B^2. \qquad (9a)$$

Using eq (9a), eq (5) and (8) become

$$S'_B = \frac{D_0 E_B^3 P_d}{4t_0} \qquad (5a)$$

$$S'_B = S_B E_B. \qquad (8a)$$

Now we assume that the tensile strength, ultimate elongation, and original thickness of the film are the same for the patch and the balloon. Equating the values of tensile strength given by eq (3) and (7) gives

$$\frac{P}{P_d} = \frac{5D_0}{4a}. \qquad (10)$$

As a is 1.25 in. in these tests,

$$\frac{P}{P_d} = D_0, \qquad (10a)$$

with D_0 in inches.

It is not always convenient to measure D_0 in the laboratory, and the flaccid length, L_0, is often measured instead. This is the length of the uninflated envelope exclusive of the neck, when the balloon is suspended vertically by the neck. It is assumed that

$$D_0 = \frac{2L_0}{\pi}. \qquad (11)$$

The Dewey & Almy Chemical Co.[5] has been inflating small balloons having an unstretched diameter of 4 in. at a temperature of −75° F. A typical bursting pressure from their data is 11 in. of water.

[5] Dewey & Almy Chemical Co. (private communication).

When these values are substituted in eq (10a), the bursting pressure of a patch cut from a similar film is found to be 44 in. of water. The average bursting pressures of patches from four production Dewey & Almy sounding balloons tested at $-76°$ F ($-60°$ C) are 47, 54, 65, and 83 in. of water. Of course, these rubber films may differ from those of the small balloons tested at the factory.

Additional tests of eq (10a) have been made by inflating pilot balloons with air at room temperature and making patch tests at room temperature on other balloons from the same lots. For example, the bursting pressure of a balloon was 0.92 in. of water, and the patch-test bursting pressure was 15.7 in. of water. By eq (10a) the unstretched diameter of the balloon is calculated to be 17 in. The balloon was not a perfect sphere when inflated just enough to remove the wrinkles, but the average horizontal diameter was measured as 16 in. The diameter calculated from the measured volume of the balloon, using the formula for a sphere, was 16.6 in.

In all these cases the bursting pressure of the patches is slightly higher than the value calculated by using the bursting pressure and flaccid diameter of the balloon in eq (10a). This difference can be attributed to the fact that the bursting pressure of the balloon does not correspond to the average bursting pressure of the patches cut from it, but to that of the weakest patch. The method of estimating the minimum bursting pressure of all the patches from the balloon is discussed in section 5.

4. Flight Equation

When a sounding balloon ascends into the atmosphere, it expands as the atmospheric pressure decreases until it finally bursts. The atmospheric pressure at burst, P_a, which determines the bursting elevation, is given by the equation

$$P_a=P_B-P_d, \tag{12}$$

where P_B is the absolute pressure inside the balloon, and P_d is the differential pressure across the surface of the balloon at burst.

P_B may be found from the ideal gas law, because helium and hydrogen behave almost like perfect gases under these conditions and as there is not enough time for very much gas to escape through the balloon film,

$$P_B=P_i\frac{T_B}{Ti}\frac{R_i^3}{R_B^3}, \tag{13}$$

where P is the absolute pressure inside the balloon, T is the absolute temperature of the gas, and R is the radius of the balloon. The subscript i refers to the initial conditions at launching, and the subscript B refers to conditions at burst.

Letting $R_B=R_0E_B$ and $R_0=\frac{L_0}{\pi}$ in eq (13) gives

$$P_B=P_i\frac{T_B}{T_i}\frac{R_i^3\pi^3}{E_B^3L_0^3}. \tag{13a}$$

The value of R_i depends upon conditions at launching. Usually the balloon is inflated until it will just lift a specified weight. Assuming that the ideal gas law holds, the relation is

$$R_i^3=\frac{3V_i}{4\pi}=\frac{3}{4\pi}\cdot\frac{RT_i(F+W)}{P_i(M_a-M_g)}, \tag{14}$$

where V_i is the volume of the balloon at launching, R is the gas constant, F is the lift, W is the weight of the balloon, M_a is the weight of a molal volume of air, and M_g is the weight of a molal volume of inflating gas. Substituting this value for R_i into eq (13a) gives

$$P_B=\frac{3\pi^2R(F+W)T_B}{4(M_a-M_g)E_B^3L_0^3}. \tag{15}$$

P_d, the differential bursting pressure across the surface of the balloon, may be found from eq (10a) and (11),

$$P_d=\frac{\pi P}{2L_0}, \tag{16}$$

where P is the bursting pressure from the patch test and L_0 is the flaccid length of the balloon in inches.

Another relation for P_d may be obtained by expressing the thickness of the rubber film in terms of other constants of the balloon and by using S'_B, the tensile strength on the final cross-sectional area, instead of P.

$$t_0=\frac{W}{\pi D_0^2\sigma}, \tag{17}$$

where σ is the density of the rubber.

Solving for P_d in eq (5a) and substituting for t_0 from eq (17), we have

$$P_d=\frac{4WS'_B}{\pi\sigma D_0^3E_B^3}=\frac{\pi^2WS'_B}{2\sigma L_0^3E_B^3}. \tag{18}$$

The equation used for predicting the performance of production sounding balloons is obtained by substituting the expressions for P_B and P_d from eq (15) and (16) into eq (12) and using appropriate values for some of the factors. Assume that the balloon is inflated to a lift of 3,000 g and that the temperature at burst is 213° K. The gas constant is 5,074 in.^{3} millibars per gram mole deg K. M_a is 28.96 g, and if the gas used is helium, M_g is 4.00 g.

$$P_a=\frac{320{,}000(3{,}000+W)}{E_B^3L_0^3}-\frac{1.57P}{L_0}, \tag{19}$$

where P_a is the atmospheric pressure at burst in millibars, W is the weight of the balloon in grams, E_B is the elongation at burst, L_0 is the flaccid length of the balloon in inches, and P is the bursting pressure from the patch test in millibars.

A form of the flight equation that is more convenient for some purposes is obtained by substituting the values for P_B and P_d from eq (15) and (18) into eq (12).

$$P_a=\frac{A(F+W)T_B-BWS'_B}{E_B^3L_0^3}, \tag{20}$$

where

$$A=\frac{3\pi^2R}{4(M_a-M_g)} \quad \text{and} \quad B=\frac{\pi^2}{2\sigma}.$$

It is possible to obtain an approximate equation that gives the flight elevation directly. The relation between elevation and pressure for the standard atmosphere [6] in the region where the balloons burst is

$$h=89.2-14.6 \log P_a, \tag{21}$$

where h is the elevation in kilometers, and $\log P_a$ is the logarithm to the base 10 of the atmospheric pressure in dynes per square centimeter.

Substituting P_a from eq (20) into eq (21), we have

$$h=89.2+43.8 \log(E_BL_0)-14.6 \log[A(F+W)T_B-BWS'_B]. \tag{22}$$

A study of this equation shows that changes in E_B or L_0 will have a pronounced influence on the bursting elevation and that proportionate changes in the balloon weight, temperature at burst, or tensile strength will have a much smaller effect. We may substitute typical values for the less important quantities and obtain an approximate equation in a simpler form. Let $F=3{,}000$ g, $T_B=213°$ K, $W=600$ g, $S'_B=7.63\times10^8$ dynes/cm^2, $R=8.314\times10^7$ ergs/mole deg K, $\sigma=1.25$ g/cm^3, $M_a=28.96$ g, and $M_g=4.00$ g. Then $A=2.47\times10^7$ ergs/g deg K, and $B=3.95$ cm^3/g. Equation (22) becomes

$$h=43.8 \log(E_BL_0)-104.0, \tag{23}$$

with h in kilometers and L_0 in centimeters or

$$h=43.8 \log(E_BL_0)-86.3, \tag{24}$$

with h in kilometers and L_0 in inches.

Both eq (19) and (24) give values that are in reasonable agreement with flight results. Equation (24) indicates that the bursting elevation is linearly related to the logarithm of the product of elongation and flaccid length. A method of determining the effective elongation and minimum patch-bursting pressure used in these equations is given in section 5.

5. Effective Elongation

In predicting the flight performance of a group of similar balloons, the elongation and the bursting pressure determined from patch tests on some of the balloons may be used in eq (19), together with the average weight and flaccid length of the balloons to be flown. In a perfectly uniform spherical balloon a test of one patch would give the ultimate elongation and the bursting pressure characteristic of the entire balloon. Actually, there is a good deal of variation in strength (due in part to variation in thickness) over the surface of a balloon. When the weakest section fails most parts of the balloon will be considerably below their ultimate elongations. Consequently, the balloon will burst at a smaller volume and a lower elevation than would be anticipated if the average ultimate elongation and the average bursting pressure of the film were used. How much lower the altitude will be depends on the amount of variation in the stress-strain characteristics of the rubber.

The effective elongation, which is used in determining the bursting volume of the balloon, may be defined as the average elongation of the entire balloon film at the differential pressure at which the weakest part will fail. The minimum bursting pressure and the effective elongation are estimated from patch-test data. A balloon may be equivalent to as many as 1,500 patches, but only a few of them are tested. The standard deviation in bursting pressure is found for the patches tested, and a multiple of this standard deviation is subtracted from the average bursting pressure to get the estimated minimum bursting pressure. In practice, it has been found that an appropriate value for this multiple is 2. Thus, the patch bursting pressure used in the flight equation is two standard deviations below the average bursting pressure of the patches tested.

For each patch tested a plot can be made of the differential pressure corresponding to various elongations. The plots for different patches from the same balloon are usually similar. Figure 3 is an example

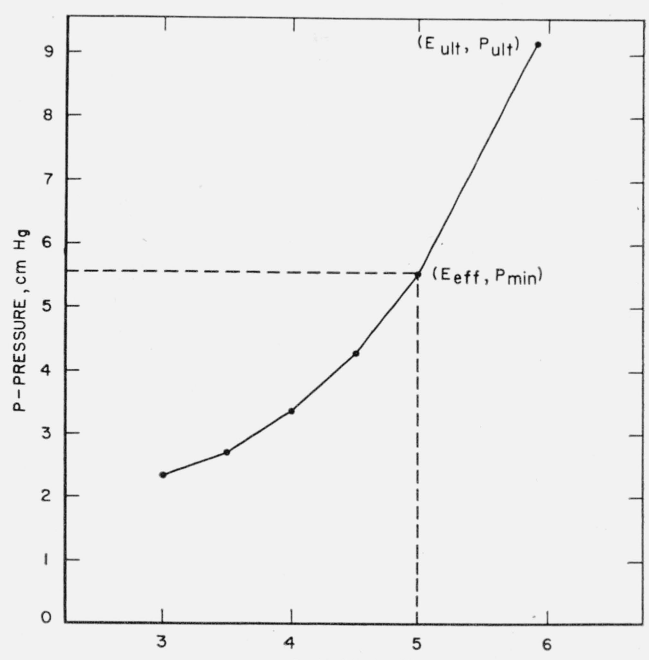

FIGURE 3. *Differential pressure versus elongation in patch tests at —60° C.*

Each point is an average for 18 patches from 1 group of balloons.

[6] Calvin N. Warfield, A tentative standard atmosphere, NACA Tech. Note 1200.

of this relationship obtained by averaging a number of patches. The curve ends at a point representing the average differential pressure and elongation at failure, that is, the average bursting pressure and the average ultimate elongation of the patches. The horizontal dashed line represents a pressure two standard deviations below the average bursting pressure. This is the estimated minimum bursting pressure in the patch test, which is related by eq (10a) to the differential pressure at which the weakest region of the balloon will fail. At that particular moment the average elongation of the balloon should have a value that can be approximated by taking the abscissa in figure 3 corresponding to the minimum pressure. The value thus obtained is the estimated effective elongation and may be used for E_B in the flight equation.

An estimate was obtained for the precision of the bursting elevations predicted from the results of patch tests at $-60°$ C on the four groups used in the special experiment described in section 6. For balloons from the same group, the standard deviation of predicted elevations was found to be 2.7 km, based on tests of three patches per balloon. The standard deviation in actual night flight elevations of balloons from the same group was 2.1 km. Thus, provided that the same number of balloons are tested as are flown, the reproducibilities of laboratory and flight tests are about the same. However, the accuracy of the laboratory values may not be as good because factors other than those included in eq (19) or (20) may cause premature failure of the balloon.

Actual flight performance may differ from that predicted on the basis of the patch test because of the action of ozone at high elevations, the concentration of stresses in certain parts of the film, such as the region where the neck joins the body of the balloon, the different rate of stretching and the different temperatures experienced in flight, or possibly because of other factors that are not yet understood. Also the distribution of patch-bursting pressures may be different for different balloons, which may cause errors in the estimation of the minimum bursting pressures and effective elongations and reduce the accuracy of the predicted elevations. Nevertheless, this method gives results that show significant correlation with flight elevations.

As mentioned before, the method outlined for obtaining the minimum patch-bursting pressure for a balloon by subtracting two standard deviations from the average value is essentially an empirical one. Theoretically, statistical methods can be used to estimate the minimum pressure. This would require certain assumptions concerning the distribution function of patch-bursting pressures so that the theory of extreme values could be applied. It would then be desirable to obtain a random sample of patches from the balloon. In the work reported here the selection of patches was not entirely random because the balloon was cut into sections and one or more patches taken from each section. The information so far obtained from the investigation is not sufficient to make use of this theoretical approach.

6. Flight Experiments

In section 4 it is shown that there should be approximately a linear relationship between the flight elevation and the logarithm of the product of elongation and flaccid length. The relation between this logarithm and flight elevations was studied on production lots of balloons flown by the Weather Bureau in regular service. The day flights of samples from 30 lots made by three different manufacturers did not discriminate between lots that had differences as judged by both night flights and laboratory tests. Data from the $-60°$ C patch test (described in section 2) showed some correlation with the night flights of samples from 18 production lots. These data are summarized in table 1. Using the ultimate

TABLE 1. *Results of laboratory tests and night flights of production lots of balloons*

Lot number	Number of flights	Median flight elevation	Average flaccid length, L_0	Ultimate elongation, $E_{ult.}$	Log ($L_0 \times E_{ult.}$)	Effective elongation, $E_{eff.}$	Log ($L_0 \times E_{eff.}$)
		km	*in*				
1	3	24.91	75.7	4.97	2.575	4.58	2.540
2	3	25.41	75.6	4.96	2.574	4.34	2.516
4	6	22.44	73.8	5.09	2.575	4.35	2.506
5	5	16.63	74.8	4.91	2.565	3.48	2.415
25	1	19.84	77.0	5.60	2.635	3.93	2.481
26	2	17.69	73.5	5.57	2.612	3.84	2.451
27	2	20.18	74.0	5.44	2.605	4.72	2.543
28	2	19.00	76.5	5.60	2.627	4.78	2.563
29	2	20.19	79.0	5.28	2.620	4.23	2.524
30	2	21.20	73.5	5.54	2.610	5.15	2.578
31	2	19.80	72.5	5.52	2.602	4.95	2.555
33	2	24.76	77.0	5.50	2.627	5.22	2.604
34	2	18.22	79.0	5.40	2.630	4.82	2.581
35	1	24.70	82.0	5.29	2.637	4.52	2.569
36	2	23.58	80.0	5.27	2.625	4.23	2.529
6N	10	25.22	76.3	6.13	2.670	5.33	2.609
7N	10	26.90	77.3	5.98	2.665	5.19	2.603
8N	21	25.03	72.0	5.92	2.630	5.43	2.592

elongation, the correlation coefficient is 0.57; with the effective elongation, it is 0.77. The probability of obtaining a value as large or larger than 0.57 by chance alone is about 2 percent; the corresponding probability for 0.77 is considerably less than 0.1 percent. The correlation coefficients were weighted to take account of the number of flights made for each lot. Only five patches from one balloon were tested for most lots. Considering the small number of flights made and the small number of patches tested for most samples, the correlation was as good as would be expected. As the data were not obtained from a systematically designed series of experiments, few conclusions regarding the factors affecting the performance of sounding balloons can be drawn from them.

In order to make a more conclusive study of these factors, a special experiment was designed. This experiment involved 120 balloons divided into four groups of 30 balloons each. These groups consisted of regular and post-plasticized (plasticized after vulcanization), balloons from each of two manufacturers. The weights and flaccid lengths of the balloons were held fairly constant within each of the four groups. The 30 balloons within each group were used as follows: 12 for day flights, 12 for night flights, and 6 for laboratory tests. The allocation of balloons for flight and laboratory test was done at random. The order in which the balloons were tested in the laboratory was also random. For the laboratory tests, six patches were cut from each balloon. Three of the patches were tested at a constant temperature of −40° C, and the other three, by the procedure given in section 2, with a temperature of −60° C at burst.

Table 2 shows the design of the flight tests for the four groups of balloons at four Weather Bureau stations. On any one day at any one station two balloons from the same group were flown; one in the daytime and one at night. Table 3 lists the average bursting elevations for balloons of each group flown at each station. The results for day and night flights are given separately. In several cases the averages reported are for two flights for a given group at a given station instead of for the three indicated by the schedule of table 2, either because of instrument failure or premature failure of the balloon. Such results were eliminated because they do not reflect the inherent characteristics of the rubber film. An analysis of variance for the data from the individual flights reveals that:

1. The day-flight results do not distinguish conclusively between the four groups of balloons. The ranking changes markedly from station to station.
2. The night-flight results are more consistent for balloons of a given group, whether the balloons are flown at the same station or at different stations.

Tables 4 and 5 give the average differential bursting pressures and ultimate elongations for the six balloons from each group in the −40° and −60° C patch tests. The average effective elongations for the balloons in each group are given in table 6. Figures 4 and 5 show plots of the average flight elevations against the logarithms of the products of elongation and flaccid length. The day flights are compared with the results from the −40° C patch test, and the night flights are compared with the results from the −60° C patch test. In figure 4 the effective elongations are used and in figure 5 the ultimate elongations. When the ultimate elongations are used the correlation is rather poor. However, if the effective elongations are used, the correlation is excellent for night flights. It is seen that the points for the day flights, using effective elongations, are not very far from the line determined by the night flights. The greater scatter of the points for day flights is not surprising because of the uncertainty of the temperature of the balloon film (discussed in section 7) and the erratic behavior of the day flights. The small range in average day-flight elevations and effective elongations of the four groups and the large uncertainties in day-flight values result in low sensitivities for the day flights and −40° C patch tests, which are not sufficient to obtain significant differences between the four groups of balloons in this experiment.

TABLE 2. *Allocation of balloons to flight stations*

W, St. Cloud, Minn.; X, Bismarck, N. Dak.; Y, Rapid City, S. Dak.; Z, International Falls, Minn.

Day of flight	Group			
	A	B	C	D
1	W	X	Y	Z
2	X	W	Z	Y
3	Y	Z	W	X
4	Z	Y	X	W
5	X	W	Z	Y
6	W	X	Y	Z
7	Z	Y	X	W
8	Y	Z	W	X
9	Y	Z	W	X
10	Z	Y	X	W
11	W	X	Y	Z
12	X	W	Z	Y

TABLE 3. *Flight results*

Average bursting elevations, in kilometers

Flight station	Group							
	A		B		C		D	
	Day	Night	Day	Night	Day	Night	Day	Night
W	22.64	23.54	25.21	18.36	21.79	24.15	27.82	20.16
X	21.00	23.35	25.26	17.64	24.95	23.68	22.43	18.02
Y	24.08	22.55	17.09	17.75	22.35	20.71	22.64	18.97
Z	19.38	25.66	23.95	19.55	24.50	22.97	22.84	19.80
Average	21.78	23.78	22.88	18.33	23.40	22.88	23.94	19.24

TABLE 4. *Laboratory results for patch tests at −40° C*

Balloon number	Group							
	A		B		C		D	
	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation
	cm Hg		*cm* Hg		*cm* Hg		*cm* Hg	
1	6.4	6.20	12.7	5.60	8.9	5.40	11.1	5.23
2	7.1	5.95	13.7	5.53	8.3	5.40	10.5	5.23
3	8.4	6.07	9.5	5.60	8.4	5.53	10.4	5.28
4	10.3	5.77	14.1	5.77	8.5	5.27	10.4	5.22
5	12.1	5.93	14.4	5.67	8.9	5.40	10.7	5.22
6	10.8	5.73	14.8	5.83	8.9	5.27	11.3	5.30
Average	9.2	5.94	13.2	5.67	8.7	5.38	10.7	5.25

TABLE 5. *Laboratory results for patch tests at −60° C*

Balloon number	Group							
	A		B		C		D	
	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation	Bursting pressure	Ultimate elongation
	cm Hg		*cm* Hg		*cm* Hg		*cm* Hg	
1	12.0	6.05	19.0	5.90	13.5	5.00	15.9	4.75
2	8.9	6.05	15.9	5.47	13.9	4.97	14.7	4.67
3	14.0	5.55	16.9	5.68	11.8	4.93	14.3	4.77
4	12.7	5.92	15.5	5.27	12.7	4.82	15.5	4.83
5	13.2	5.48	16.8	5.60	13.9	4.73	15.9	4.83
6	10.8	6.07	18.2	5.23	13.5	4.92	14.8	4.68
Average	11.9	5.85	17.0	5.52	13.2	4.90	15.2	4.76

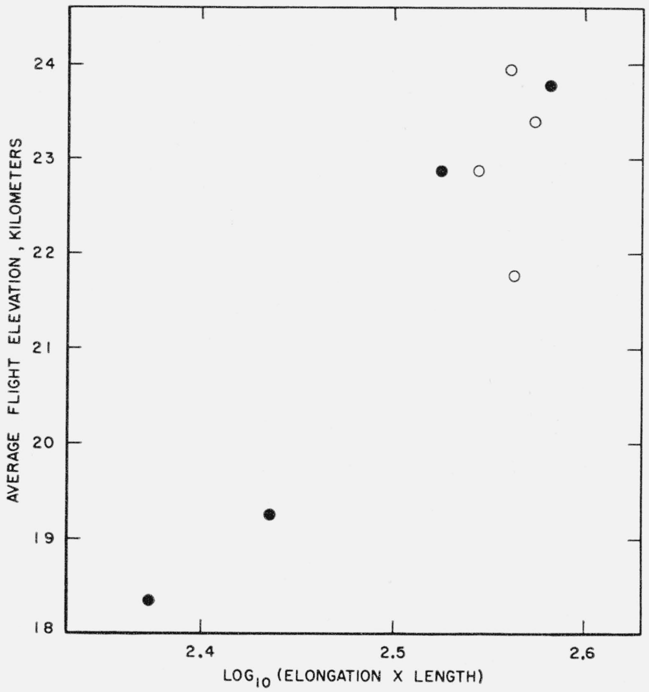

FIGURE 4. *Correlation between flight elevation and effective elongation.*

○, day flights and patch tests at −40° C; ●, night flights and patch tests at −60° C.

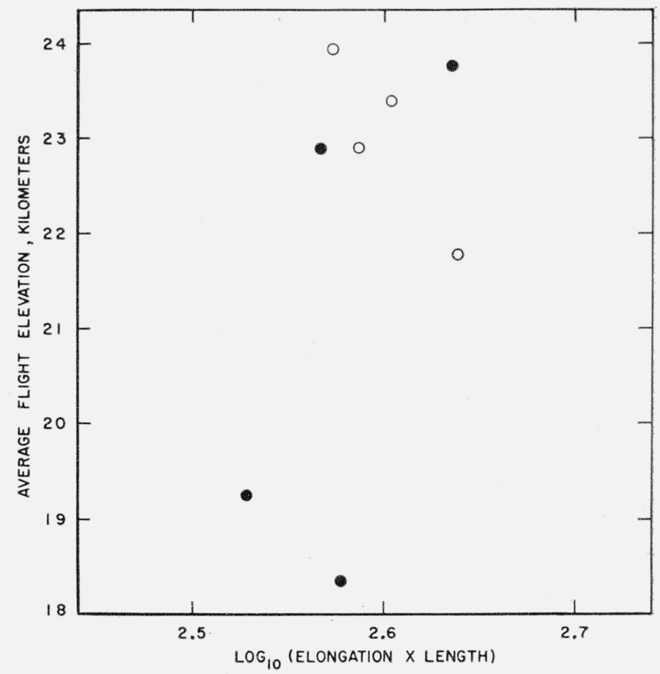

FIGURE 5. *Correlation between flight elevation and ultimate elongation.*

○, day flights and patch tests at −40° C; ●, night flights and patch tests at −60° C.

TABLE 6. *Estimation of temperature difference between day and night flights*

Group	Ultimate elongation from patch test at—		Effective elongation from patch test at—		Flaccid length		$T_D - T_N$	
	−40° C	−60° C	−40° C	−60° C	Day flights	Night flights	From ultimate elongation	From effective elongation
					in.	*in.*	° *C*	° *C*
A	5.94	5.85	4.99	5.16	73.3	74.0	−38	17.6
B	5.67	5.52	5.15	3.44	68.1	68.6	232	12.8
C	5.38	4.90	5.01	4.45	74.8	75.3	9	6.8
D	5.25	4.76	5.11	3.85	71.3	70.9	46	14.4

7. Temperature of Balloon During Flight

Sounding balloons usually attain higher elevations during the day than at night. For the post-plasticized balloons that have been developed in the last few years, the difference between day and night flights is not large, but some regular balloons have been tested that flew satisfactorily in the daytime but flew very poorly at night. This variation between day and night flights appears to be due to a difference in the temperature of the balloon film. The temperature of the air in the stratosphere is about the same day or night. However, during the day the balloon film is heated by the sun's radiation and should be at a higher temperature than its surroundings. (Although the thin neoprene film is fairly transparent to visible light, it absorbs strongly in the ultraviolet and infrared regions of the spectrum.) At night the gas inside the balloon is cooled by expansion, and the temperature of the balloon film should be slightly below that of the air.

Groups of balloons have been flown both day and night, and patch tests have been made at two different temperatures. From the differences in day- and night-flight elevations, and the rates of change of the effective elongation with the temperature of the patch test, the balloon films have been estimated to be anywhere from 5° to 25° C warmer during the day than at night.

The method of estimating this temperature difference will be illustrated for the four groups of balloons in the planned flight experiment discussed in section 6. The necessary equations are

$$h_D - h_N = 49 \log_{10}\left(\frac{E_D L_D}{E_N L_N}\right), \tag{25}$$

$$\frac{T_D - T_N}{20} = \frac{E_D - E_N}{E_{-40} - E_{-60}}. \tag{26}$$

Equation (25) is derived from an expression similar to eq (24) but with different values of the constants. The subscript D refers to conditions during day flights, and the subscript N refers to conditions during night flights. Equation (26) is obtained by assuming that the elongation varies linearly with the temperature. The subscripts −40 and −60 refer to the temperatures at which the elongations were measured in the patch test.

The average flaccid lengths of the balloons flown during the day and flown at night and the differences in average day and night flight elevations may be substituted in eq (25). Then the elongation found from the patch test at −60° C is substituted for E_N, and eq (25) may be solved for the corresponding value of E_D. Using these values of E_D and E_N in eq (26), we may solve for the difference in temperature of the balloon film during day and during night flights. Table 6 gives the data used and the estimated temperature differences made in this manner for the four groups of balloons in the planned flight experiment, using both ultimate and effective elongations. Groups B and D show the most rapid change in effective elongation with the temperature, and should give the best estimates of the temperature difference. The values calculated from the effective elongations are more consistent than those calculated from the ultimate elongations. Furthermore, the balloons of group A burst at a lower average elevation in the daytime than they did at night; this result is predicted from the effective elongations, but not from the ultimate elongations at the two temperatures.

No inexpensive and reliable method of measuring the temperature of the balloon film itself during flight is known, but the Weather Bureau has made five flights in which the temperatures inside and outside of the balloon were measured. Radiosondes were modified to give three temperature readings. The air temperature was measured in the normal manner in a duct in the radiosonde box. Two additional temperature readings were obtained in place of the relative-humidity circuit. These readings were taken inside the balloon, which was carrying the radiosonde at positions near the top and near the bottom of the balloon. For night flights ordinary thermistors were used on all positions. For day flights white-coated thermistors (approximate diameter of 0.075 in.) were used inside the balloon to minimize the heating effect of solar radiation. The flights were made during December and January. No corrections were made to the thermistor readings for night flights. For day flights the air temperatures were corrected for errors due to solar radiation according to standard Weather Bureau practice. No corrections were made for the errors due to solar radiation on the thermistors inside the balloon, because the exact corrections are not known for this type of exposure (shielding from solar radiation by the rubber film and very little ventilation).

At night the temperature of the gas inside the balloon near the top averaged about the same as that of the outside air and the temperature inside the balloon near the bottom averaged about 4 deg C colder than the outside air. For day flights at an elevation of 16 km the indicated temperatures inside the balloon were 17 deg C warmer than the surrounding air near the top and 15 deg C warmer near the bottom. At an elevation of 22 km, the indicated temperatures inside the balloon were 23

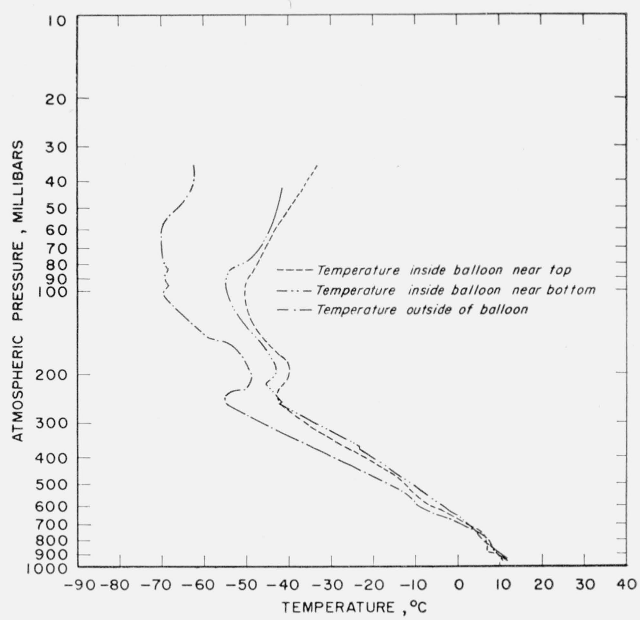

FIGURE 6. *Temperatures inside and outside of a post-plasticized balloon during a day flight.*

deg C warmer near the top and 22 deg C warmer near the bottom than the outside air. Figure 6 gives a record of one of the day flights.

The temperatures indicated by the thermistors inside the balloon are estimated to be no more than 3 deg C warmer than the surrounding gas during the day flights. It seems probable that the daytime temperature of the rubber film itself is not very different from that indicated by the thermistors inside the balloon. Therefore, it may be assumed that the rubber film is warmer than the air during day flights and that the temperature difference increases with the elevation. At normal bursting elevations of 20 to 30 km, the film is probably 20 to 30 deg C warmer than the surrounding air during the day, whereas at night the rubber film may average 0 to 4 deg C colder than the surrounding air. Although the number of flights is too small to estimate the reliability of these results, there appear to be no inconsistencies between duplicate flights.

8. Summary

Because the Navy prefers to use a single type of balloon for both day and night flights and because the night flight is usually the more severe test, most of the patch tests were made at −60° C, following the procedure given in section 2. This temperature is approximately that of the rubber film at the time of burst in a night flight. The comparison of night-flight elevations with the results from the −60° C patch test indicates that the estimated effective elongation is a better measure of the quality of a balloon than the average ultimate elongation. A simple and economical ground test that can replace flight tests completely is not yet available. However, ground tests should be useful in controlling manufacturing processes, in determining whether experimental compounds might make satisfactory balloons, and in rejecting balloons of inferior quality. Planned flight experiments, combined with more extensive ground tests, may add to our knowledge of the factors that affect the performance of sounding balloons.

The flight tests for this work were made by the U. S. Weather Bureau through the cooperation of Herbert W. Rahmlow and F. P. Williams, of the Radiosonde Section, and of Jeff D. Ardoin, Silver Hill, Md., Weather Station. The temperature-measuring flights were planned with the aid of the Engineering, Upper Air Section of the Weather Bureau. The modification of the radiosondes and the flights were made by Christos Harmantas, Mary W. Hodge, Joseph S. Szokolszky, and Walter D. Smith of that section. At the National Bureau of Standards, Russell J. Capott, Richard S. Cleveland, Joseph J. Hamm, Ellis O. Knox, Elmer A. Koerner, John E. Pugh, Louis Schuman, Elmer W. Zimmerman, and others have contributed to the project.

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