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EFFECT OF SOLAR RADIATION UPON BALLOONS

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I. INTRODUCTION

The action of sunlight upon a balloon affects both the temperature and the life of the fabric of which the balloon envelope is constructed, and the resulting temperature changes affect both the operation of the balloon and its gas permeability. It is a matter of interest as well as importance, therefore, to understand the character and magnitude of these effects so that they may be intelligently controlled. Sunlight affects the operation of the balloon because changes in its character and amount cause fluctuations in the temperature of the balloon envelope and consequently in the temperature and lifting power of the gas contained in it. The reduction of such changes to a minimum makes for stability and efficiency in the operation of the balloon. The radiation characteristics will be discussed first, therefore, from the standpoint of their effect upon temperature rise.

The other effect of the sunlight, that of its photo-chemical action upon the fabric, results in decreasing the strength of the fabric and causing deterioration of the rubber. This eventually results in increasing the porosity of the fabric to an inadmissible extent. The increase in temperature of the fabric caused by the radiation absorbed also increases its permeability as will be explained later.

The nature of these effects, their measurement and their application to practical aeronautics, will be discussed in the following sections. The treatment of the subject has been simplified for the benefit of those readers who are not conversant with the physics of the problem.

II. SOLAR RADIATION

Before discussing its relation to aeronautics a short summary of the characteristics of solar radiation, which are essential to an understanding of the problem, is included for the reader's convenience. It is customary to classify solar radiation qualitatively into three groups, ultra-violet, visible, and infra-red radiation, depending on its constituent wave lengths. The visible part of the spectrum is comprised approximately between the wave lengths 0.40μ to 0.72μ ($\mu = 0.001$ mm); radiation of wave lengths less than those of the visible violet is termed ultra-violet; radiation of wave lengths greater than those of the visible red is termed infra-red.

The intensity of the radiant energy from the sun varies in different parts of the spectrum. It is a maximum in the blue-green, decreases rapidly toward the red and still more rapidly toward violet. Curve *A* in Fig. 1 shows graphically the general distribution of energy in the solar spectrum before entering the earth's atmosphere. Inside of the atmosphere both the total intensity and the relative spectral distribution are changed owing to diffuse reflection and absorption by the atmospheric gases, water vapor, and dust particles.

Neglecting the narrow absorption bands which cause the curve to appear saw-toothed, the general energy distribution as observed on Mount Whitney (altitude 4420 m) is shown by curve *B*, on Mount Wilson (altitude 1730 m) by curve *C*, and at Washington, D. C., by curve *D*. Further discussion of the causes of these effects can be found in the excellent literature on the subject, but it is worth noting here that the shorter wave lengths are absorbed most by the passage through the atmosphere, and the longer

wave lengths are absorbed least. This causes an effective shift of the region of maximum intensity toward the red and a diminution of the ultra-violet radiation to a very small value at the earth's surface. The curves drawn in solid lines in Fig. 1 are for the sun at the zenith. With the sun at any other point than the zenith, the air path through which the radiation must travel is increased and the radiation suffers a further loss of intensity. Curves *E* and *F* show the relative intensity at Washington when the sun is at angles of 60° and 70°, respectively, from the zenith.

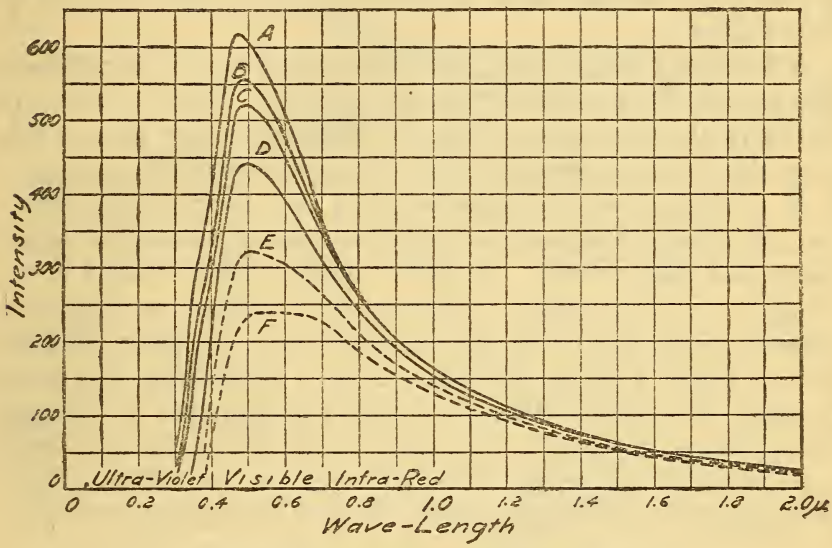

FIG. 1.—*Relative intensity of solar radiation*

A, Outside earth's atmosphere; *B*, on Mount Whitney (altitude, 14500 feet); *C*, on Mount Wilson (altitude, 5680 feet); *D*, Washington, D. C. (sun at zenith); *E*, Washington, D. C. (sun at 60° from zenith); and *F*, Washington, D. C. (sun at 70° from zenith). Data obtained from Smithsonian Physical Tables.

These curves refer only to the relative intensity of the solar radiation, but in order to correlate the temperature of a body with the radiation falling on it, it is necessary to know in absolute measure the intensity of the radiation. The rate at which radiant solar energy would be received at the earth, provided there were no atmospheric absorption, has been the subject of much investigation in recent years. The evidence indicates that the solar constant (C_0), as this rate is called, is subject to periodic variations of about 7 per cent, but when the earth is at mean solar distance the average value is:

$$C_0 = 1.93 \text{ g cal. per cm}^2 \text{ per minute}$$
$$= 3.22 \times 10^{-2} \text{ g cal. per cm}^2 \text{ per second}$$
$$= 1.34 \times 10^{-1} \text{ watts per cm}^2$$

Owing to the absorption and diffusion by the atmosphere as mentioned above, this value is considerably reduced at points inside the atmosphere. The following values have been observed under favorable conditions at the points named:

Estimated for no atmosphere	C_0=1.93
Mount Whitney (4420m)	C =1.78
Mount Wilson (1730m)	=1.64
Washington	=1.35

These values are not maximum values, but are representative of clear, dry, summer days. A value of 1.51 has been observed at Washington.

It is evident that for any given time the value of C at different altitudes could be represented by a curve. Such a curve is shown in the first part of Fig. 2. Two curves are shown; one gives the values at noon, the other at approximately 8 a. m. or 4 p. m. Both curves are computed for a July day with sky cloudless, of average clearness and with an average amount of water vapor and dust present. At earlier or later hours than 8 a. m. and 4 p. m., respectively, the intensity decreases very rapidly; between those hours the solar intensity for any given altitude will be found between the two curves. Accordingly the solar intensity will usually either be within the limits set by the two curves or be negligible. The data on the solar constant have been furnished us through the courtesy of the authorities of the Smithsonian Institution, to whom our acknowledgments are due.

III. ATMOSPHERIC CONDITIONS

The effect of air pressure, temperature, and wind velocity upon the temperature rise and operation of balloons makes it also important to have a knowledge of the variation of these factors with change in altitude. There are, of course, certain day-to-day and seasonal variations in these conditions and they also vary from place to place, but the average conditions show remarkable uniformity. The values shown in Fig. 2 represent average conditions in latitudes 35° to 40°. The values of air temperature were taken from published observations of measurements with sounding balloons at Munich, Strasbourg, Trappes (near Paris), and Uccle (near Brussels). It will be noted that the average temperature gradient for summer and winter is approximately the same. The dotted line shows the maximum temperatures observed through the summer months; they have very little effect, however, in changing the average temperature gradient,

and usually diurnal changes are not found above 2000 m. For a more detailed d'scussion of this subject, the reader is referred to

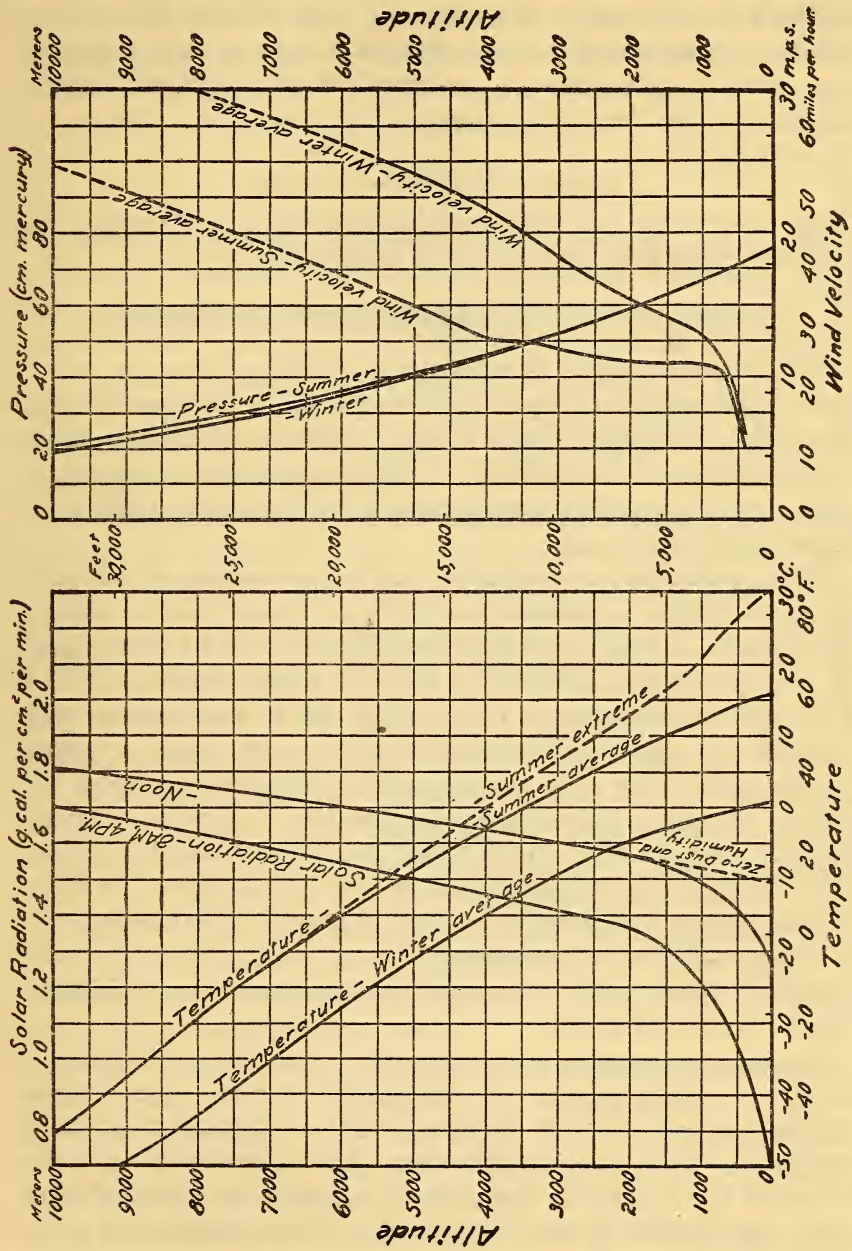

FIG. 2.—*Variation of temperature, solar radiation, barometric pressure, and wind velocity with altitude*

the series of papers by W. J. Humphreys, of the Weather Bureau, as published in the Journal of the Franklin Institute.[1] The data

[1] J. Franklin Institute, 184, p. 167; 1917.

on barometric pressure and wind velocity shown in Fig. 2 were also furnished by the Weather Bureau, to which acknowledgment is made for the use of this material. No reliable data on the variation of wind velocity with altitude above 5 km are available, but above this elevation the velocity is known to bear a definite relation to the decreasing density, which relation is known as Egnell's law.[2]

$$\text{Density} \times \text{Velocity} = \text{Constant}$$

These observations on wind velocity were made in Nebraska and are characteristic of the latitude of this country.

IV. RADIATION CHARACTERISTICS OF FABRICS

The observed effects of sunlight on a balloon must be due in part to the radiation properties of the fabric forming its envelope. The fabric, therefore, bears a direct relation to the operating characteristics of the balloon. It will be advisable, however, to discuss first the radiation properties of balloon fabrics quite apart from their intended use.

When radiant energy is incident upon any surface a fraction of all wave lengths is reflected, a fraction of most wave lengths is absorbed and a fraction of some wave lengths may be transmitted. In the case of such surfaces as those of balloon fabrics, there is what may be considered a fourth effect due to the fact that such surfaces are not homogeneous and give rise to what is termed "body color." In this last case the radiation penetrates the surface and then suffers internal reflections and refractions and emerges stripped of the rays which are most strongly absorbed. It is obvious that only the absorbed energy can affect the fabric (causing either a chemical or a physical change), for the remainder is either reflected or transmitted unchanged. It is, then, this absorbed energy, and the absorbing property of the fabric in which we are interested.

The absorbed radiant energy appears in the fabric principally in the form of heat energy. A small fraction may cause a direct chemical change, but in the case of balloon fabrics this part is negligible. The direct measurement of the fraction of radiation absorbed is not possible, but since all radiation not absorbed must leave one surface or the other it may be considered as either reflected or transmitted, and if these parts can be measured in terms of the incident radiation, then the fraction absorbed can be

[2] Humphreys, Mon. Weath. Rev., 44, p. 14; 1916.

found. Consider a case where there is a rate of incident radiant energy E, then if a fraction R is reflected, a fraction F is transmitted (where transmission is defined as a fraction of the incident rather than the entering radiation), and a fraction A is absorbed, the following relation is obvious:

$$RE + FE + AE = E \tag{1}$$

or

$$R + F + A = 1 \tag{2}$$

and

$$A = 1 - (R + F) \tag{3}$$

Thus the absorption is given in terms of the transmission and reflection and the quantity AE represents the rate at which heat will be generated in the fabric. A fraction of this heat will be lost by conduction and convection, while another portion will be reradiated. The portion reradiated depends upon a radiation property of the surface, called the emissivity, which will be discussed later. The magnitudes and interrelations of these factors determine the temperature rise of the fabric.

The general method for determining the reflecting power of any surface is to measure the energy (radiant power) of a beam of light before and after reflection from the surface. The ratio of these values gives the reflecting power for the light used as a source. The apparatus used for making these measurements was devised by Dr. W. W. Coblentz,[3] of this Bureau, and we are indebted to him for the loan of the original apparatus and his assistance in making the preliminary measurements. The method in brief was to measure the energy of a uniform beam of light by means of a linear thermopile. The energy of the same beam was then measured after reflection at normal incidence from a sample of the fabric under test. Since the reflection from a balloon fabric is largely diffuse it is necessary to use a light-gathering device in order to measure the reflected radiation. Accordingly the reflected light was brought to focus upon the thermopile by means of a silvered hemispherical mirror.

The transmission was determined with the same apparatus with some modifications. The method was to measure the energy of the beam of sunlight before and after passage through the fabric, the transmitted light being collected and brought to focus on the thermopile by the hemispherical mirror as before.

In measuring both the reflecting power and the transmitting power it is necessary to eliminate the effect of any energy reradiated from the fabric. In some measurements [4] of this kind on balloon

[3] Bulletin Bureau of Standards, 9, p. 283; 1913.

[4] See for example, Stern, Zs. f., Flugtechnik, 6, p. 145; 1915.

fabrics which have come to our attention, erroneous conclusions have been reached owing to neglect of this precaution. The reradiated energy was prevented from reaching the thermopile by covering the latter with a thin glass plate which was opaque to wave lengths greater than 4.5 μ, which wave lengths comprise the greater part of the reradiated energy.

Because of the difficulty of using a moving body, such as the sun, as a source of radiation for measurements where of necessity an interval of time existed between the measurements of incident and reflected light, solar radiation was used in only a few of the measurements. A fair substitute for the sun was found by using the radiation from a nitrogen-filled tungsten lamp transmitted by a 2-per cent solution of cupric chloride,[5] 2.5 cm in thickness. After passing through the cupric chloride solution, the light from the single, straight filament of the lamp was brought to a focus on the sample or thermopile by means of a triple-achromatic lens.

The results of some of the reflection and transmission measurements which were made with the above apparatus are given in Table 1. These particular results were selected because the fabrics on which they were obtained were representative of the kinds of fabric used. The values given in the column labeled "absorption" were calculated from equation 3; the percentages of light reflected, transmitted, and absorbed must, of course, total 100 per cent. The values for the temperature increase in sunlight will be considered later.

Notes Regarding Measurements.—While the spectral distribution of energy in the radiation from the lamp after passage through cupric chloride solution is somewhat similar to that of sunlight, yet it is not as rich in the shorter wave lengths. The solar radiation reaching the earth's surface, as shown in Fig. 1, has a maximum intensity at about 0.5μ while that of the radiation used in the reflection and transmission measurements has a maximum near 0.6μ.

It was noticed that without exception, where measurements were made, the reflecting power for sunlight was less than for the light used. This was also true for the transmitting power, with but one exception, in the case of the fabric colored with lamp black, which observation was in all probability an error.

[5] Bulletin Bureau of Standards, 7, p. 619; 1911.

TABLE 1.—Radiation Characteristics of Balloon Fabrics and Their Increase in Temperature When Exposed to Sunlight

[Except where stated otherwise all fabrics are of two-ply construction with an outer surface or coating of the character indicated.]

No.	Description of fabric	Sample of fabric	Radiation from Tungsten lamp after passage through 2.0 per cent solution of $CuCl_2$			Radiation from sun; solar intensity, 1.4 g cal. per cm^2 per min. Temperature rise above air temperature of 25° C
			Reflection	Transmission	Absorption	
			Per cent	Per cent	Per cent	°C
1	Goodyear airship fabric after 60 day's exposure		54.6	0.0	45.4	22.1
2	Goodyear airship fabric; aluminum coated		50.7	0.0	49.3	.....
3	Experimental airship fabric; aluminum coated		46.9	0.0	53.1	22.9
4	Goodyear fabric; same as No. 1 before exposure		44.9	0.0	55.1	23.0
5	Experimental airship fabric; aluminum coated		40.1	0.0	59.9	24.5
6	Aluminum coated fabric covered with nitrocellulose "dope"		32.4	1.4	66.2	.....
7	Aluminum coated fabric dusted with talc		22.6	0.1	77.3	.....
8	Ballonet fabric; uncoated cloth surface		42.2	11.8	46.0	19.9
9	Experimental single-ply fabric; pure gum coating		39.2	12.4	48.4	.....
10	French airship fabric; cloth surface dyed chrome yellow (1916)		41.9	3.1	55.0	20.7
11	Goodrich kite fabric; 30 days' exposure; light brown rubber coat		26.1	2.6	71.3	25.5
12	Goodyear kite fabric; 30 days' exposure; light gray rubber coat		19.3	2.8	77.9	29.0
13	Goodrich kite fabric No. 11, before exposure		19.4	2.4	78.2	30.0
14	Fabric from model balloon used in this investigation		15.0	4.1	80.9	(40.4)
15	U. S. Rubber Co. kite fabric; 30 days' exposure; olive green rubber coating		12.1	0.6	87.3	32.4
16	Experimental fabric; cloth surface dyed olive drab		6.5	3.8	89.7	34.1
17	Experimental fabric; dark gray rubber coating		8.3	0.0	91.7	36.0
18	Experimental single-ply fabric; black rubber coating		5.7	0.2	94.1	37.4
19	Experimental fabric; dark green rubber coating		5.2	0.0	94.8	39.0

TABLE 2.—Reflecting and Transmitting Power of Balloon Fabric for Different Sources of Radiation

[Except where stated otherwise all fabrics are of two-ply construction with an outer surface or coating of the character indicated.]

No.	Description of fabric	Reflection			Transmission		
		Sun $\lambda_m=0.5\mu$	Tungsten lamp, cupric chloride filter $\lambda_m=0.6\mu$	Tungsten lamp, "electric-smoke" glass filter $\lambda_m=1.5\mu$	Sun $\lambda_m=0.5\mu$	Tungsten lamp, cupric chloride filter $\lambda_m=0.6\mu$	Tungsten lamp, "electric-smoke" glass filter $\lambda_m=1.5\mu$
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
3	Experimental airship fabric; aluminum coated	32.7	46.9	.....	.....	0.0	.....
5	Experimental airship fabric; aluminum coated	29.5	40.1	.....	.....	0.0	.....
4	Goodyear airship fabric; aluminum coated	.....	44.9	54.3	.....	0.0	0.0
20	Goodrich airship fabric; aluminum coated	.....	50.5	61.0	.....	0.0	0.0
21	Experimental fabric; green pigmented-rubber coat	.....	18.8	16.4	.....	2.3	.....
22	Experimental fabric; dark-red pigmented-rubber coat	.....	11.3	13.9	.....	0.2	.....
23	Goodyear kite fabric; olive-drab rubber coat (1917)	.....	10.9	12.1	.....	0.7	.....
9	Experimental single-ply fabric; pure gum coating on both sides	.....	39.2	.....	9.1	12.4	16.1
18	Experimental single-ply fabric; black-rubber coating on both sides	.....	5.7	.....	0.4	0.2	.....
24	Thin sheet rubber, known as "rubber dam"	.....	.....	.....	.....	34.0	55.0

This difference in reflecting and transmitting power for radiation from different sources is shown by the results in Table 2. In this table, the reflection and transmission for radiation from the sun and from a tungsten lamp, using a cupric chloride solution as a filter, and also an "electric-smoke" glass filter are compared. The electric-smoke glass is practically opaque [6] to light in the visible region, but has a high transmission for the infra-red radiation; when combined with the tungsten lamp the radiation of maximum intensity was shifted to about 1.5μ. It will be noted that the reflection for this radiation was higher than for either of the other sources. Fabric No. 21 forms an exception to this statement; the region of maximum reflection for the green-rubber coating of this fabric is nearer 0.6μ than 1.5μ.

[6] Bulletin Bureau of Standards, 14, p. 666; 1918.

It may be concluded from the above data that the reflection and transmission generally increase as the wave length of the radiation of maximum intensity increases, and that accordingly all similar measurements using the lamp as a source will be higher than they would be for sunlight. However, the relative reflection and transmission remain about the same for each of the sources and the measurements give a reliable comparison of the different fabrics.

The question immediately arises as to how far in the infra-red the reflecting power would continue to increase. It was not considered that, for this work, the results would justify the time required for actual measurement on the fabrics in question, but a fair idea as to the infra-red characteristics can be formed from the work of previous investigators on other materials. Coblentz[7] has investigated the diffuse reflecting power of several pigments and kinds of cloth for several spectral regions in the visible and infra-red. In almost every case the reflecting power was found to be greater at 0.95 μ than at 0.60 μ. In the region of 4.4 μ, however, the reflecting power was much smaller and at 8.8 μ was still smaller. It seems probable, then, that a maximum reflection exists in the spectral region of 1 to 4 μ. Also, inasmuch as the nonmetallic surfaces exhibit body color, a maximum apparent reflection would be expected in the region of the maximum transmission[8] of the dyes, pigment particles, cellulose, and rubber composing the fabric. Most of the dyes examined[9] have a maximum transmission near 2 μ, though it remains high far into the infra-red. The transmission of both cellulose[10] and rubber[11] is a maximum in the region of 1 to 2 μ and at 3 μ decreases to nearly zero. From these facts it is reasonable to conclude that the region of maximum diffuse reflection of balloon fabrics is in the region of 1 to 2 μ.

The aluminum-coated fabrics which have recently been developed present an exception to the foregoing statements. These fabrics must have a pure metallic reflection decreased by a nonselective absorption due to the numerous small interspaces. The metallic reflection is low in the ultra-violet region, increasing through the visible and, in the case of aluminum, reaches a value of over 90 per cent in the infra-red.

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[7] Bulletin, Bureau of Standards, 9, p. 283; 1913.

[8] See page 8.

[9] Johnson and Spence, Phys. Rev., 5, p. 349; 1915.

[10] Coblentz, Publication No. 97, p. 42, Carnegie Institute of Washington; 1908.

[11] Coblentz, Publication No. 65, p. 66, Carnegie Institute of Washington; 1906.

The diffuse transmission is of less importance, in the case of most balloon fabrics, because of its small value. For some of the single-ply experimental fabrics the transmission was found to be greater in the infra-red, this being due, no doubt, to the increase in transmission of gum rubber and cellulose in that spectral region, as mentioned above. A sample of rubber dam (No. 24) was found to increase in transmission from 34 per cent for the cupric chloride filter to 55 per cent for the electric-smoke glass, which partially confirms the conclusion regarding the increase in the region of the infra-red.[12]

The significance and application of the reflection and transmission measurements will be discussed in a later section of this paper in connection with the consideration of the temperature of a balloon when exposed to sunlight. We are indebted to Dr. W. W. Coblentz for suggesting this method of investigation which gives an independent check on our temperature measurements and supplies us with new data, not heretofore obtained by direct measurement.

V. TEMPERATURE OF BALLOONS

The radiation characteristics of balloon fabrics are of interest because of their relation to the temperature of the balloon, of which they form the envelope, and also their relation to the buoyancy of the contained gas. The temperature and the corresponding lifting power of the gas are determined, in fact, solely by the temperature of the fabric, for the absorption of radiation by the gas is negligible.

The temperature of a thin sheet of material upon which radiation is falling, is dependent on (1) the intensity of the radiation; (2) the absorbing power of the surface for the incident radiation; (3) the emissivity of the surface at the temperature in question; (4) the loss of heat by conduction and convection, both from the front and back surfaces.

1. TEMPERATURE FOR RADIATION EQUILIBRIUM

When a thin sheet of material is in thermal equilibrium with its surroundings, all additions of heat are balanced by losses of heat. In order first to investigate the temperature of the fabric when in radiation equilibrium, under conditions where there is no loss of heat by conduction or convection, the case of a surface in a vacuum may be considered.

[12] See Publication No. 65, p. 66, Carnegie Institute of Washington, for transmission curve of rubber; 1906.

The radiant energy (E_1) absorbed in sunlight will then be approximately:

$$E_1 = A_1 E_s \tag{4}$$

where A_1 is the coefficient of absorption in the spectral region of maximum solar intensity (0.5μ), and E_s is the rate at which radiant solar energy is incident upon the surface.

Presumably the radiation (E_2) from each surface of the material is purely a thermal radiation, and therefore in full agreement with the Kirchhoff law, and we may write for each surface,

$$\frac{E_2}{A_2} = E \tag{5}$$

over a range of wave lengths where the coefficient of absorption (A_2) of the surface in the spectral region of maximum intensity of the reradiated energy does not materially change and where E is the total emissivity of a black body. But from the Stefan-Boltzmann law:

$$E = \sigma T^4 \tag{6}$$

where σ is the constant of total radiation for a totally absorbing body and T is the absolute temperature. Then for a single surface of the material:

$$E_2 = A_2 \sigma T^4 \tag{7}$$

and for both surfaces:

$$2 E_2 = 2 A_2 \sigma T^4 \tag{8}$$

For thermal equilibrium the reradiated energy must equal the absorbed energy, or E_1 must equal $2 E_2$, therefore:

$$A_1 E_s = 2 A_2 \sigma T^4 \qquad \text{or} \tag{9}$$

$$T = \left(\frac{A_1}{A_2}\right)^{1/4} \cdot \left(\frac{E_s}{2\sigma}\right)^{1/4} \tag{10}$$

The last term of this equation, $\left(\frac{E_s}{2\sigma}\right)^{1/4}$, gives the temperature of a totally absorbing, or "black body." Therefore, any other body in a vacuum will come to equilibrium at an equal, higher,[13] or lower temperature according to whether the ratio [14] of A_1 to A_2 is equal to, greater, or less than 1.

In order that the increase in temperature of a fabric may be made a minimum, the above ratio should be made as small as possible, that is, A_1 should be small and A_2 large. In other words, the fabric should absorb as little as possible of the solar radiation and reradiate that absorbed with a minimum rise in

[13] No such case is known.

[14] Ratio of absorbing power for wave lengths of 0.5μ to absorbing power for wave lengths of 9μ.

temperature. In most instances, as will be shown later, the absorption for sunlight (A_1) is the important factor in determining the temperature rise for radiation equilibrium. For transparent bodies A_1 is zero and the radiation causes no rise [15] in temperature.

Of all opaque surfaces investigated, zinc oxide [16] fulfills the above requirements most perfectly. A_1 for zinc oxide is about 18 per cent and A_2, 97 per cent. The temperature would, therefore, be $\left(\frac{18}{97}\right)^{1/4}$, or 66 per cent, of the absolute temperature that a black body would reach under similar circumstances, in the hypothetical case which was assumed, that is, in a vacuum.

2. HEAT LOSSES

The effective value of the solar radiation falling upon the upper surface of the balloon, which will have to be reradiated from the balloon if thermal equilibrium is to be reached, will be diminished (1) by energy reradiated to the lower surface of the balloon, (2) by conduction through the contained gas, and (3) by losses by conduction and convection to the atmosphere.

(a) *Reradiation to Lower Surface.*—The upper surface of the balloon radiates energy to the lower surface and the lower surface in turn radiates energy to the upper surface. It can be shown that, in a balloon, the resultant transfer of energy from the hotter upper surface to the cooler lower surface is approximately

$$E = 1/2\ (A_2\sigma\ T^4 - A_3\sigma\ T_0^4) \qquad (11)$$

where T and T_0 are the absolute temperatures of the upper and lower surfaces, respectively. If the upper and lower surfaces are of the same fabric

$$A_2 = A_3$$

because the radiation from each will be approximately in the same spectral region and the equation can be simplified to

$$E = 1/2\ A_2\sigma\ (T^4 - T_0^4) \qquad (12)$$

where T_0 is the absolute temperature of the lower surface of the balloon.

(*b*) *Conduction Through the Gas in the Balloon.*—The loss by conduction from the upper surface through the gas in the balloon is negligible at all times. For a balloon having a diameter of 10 m and with a difference in temperature between the surfaces of 25° C, we have computed the loss by conduction to be less than 1 per cent of the total loss of heat.

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[15] As an illustration of such a case, a large soap bubble, blown with gas in the shade, showed no change in buoyancy on being fanned into the sunlight.

[16] Coblentz. Bulletin Bureau Standards, 9, p 313; 1913.

(*c*) *Loss by Convection to the Atmosphere.*—The determination of the temperature of a balloon is further complicated by the loss of heat by conduction and convection to the atmosphere. Furthermore, the convection is dependent upon so many variables that no simple solution of the problem seems possible. The results of all recent investigators of this subject can, however, be expressed in the general form

$$H = ktv^n \tag{13}$$

where H is the heat lost in gram-calories per square centimeter per second, t is the difference in temperature between the surface and the surrounding air in degrees centigrade, v is the wind velocity in centimeters per second, k is a constant dependent on the properties of the gas, and n is a constant apparently dependent on the form of the surface, and for large ranges of velocity, on the velocity also. It has been pointed out [17] that the experimenters using small wires found the value of n to be approximately 0.5, while the few experimenting with much larger cylinders found n equal to 1. Hughes also found that the value of n for a small stream-line surface is 0.62 [18] and that for a difference in temperature of 90° C and a wind velocity of 13 m per second, the relative losses of heat for various surfaces were as follows:

Shape of tube	Loss of heat
Stream-line surface	100
Cylindrical surface, area=that of stream-line surface	85
Cylindrical surface, diameter=maximum diameter of stream-line surface	40
Cylindrical surface, air resistance=that of stream-line surface	13

It seems probable therefore, that a stream-line balloon is well adapted for dissipating a maximum amount of heat at this velocity. The composition or condition of surface apparently has little effect as long as the surface condition does not cause turbulence.

At this point it is perhaps worth while to call attention to the fact that although it is important in hot summer weather to keep the temperature below a point that will cause high gas permeability and increased deterioration of the fabric, it is not this absolute temperature that is of primary importance, in so far as stability of operation is concerned. Rather it is the magnitude and rapidity of the changes in temperature caused by changing solar intensity (due to clouds) or by changing wind velocity, or the

[17] Hughes, Phil. Mag., 31, p. 126; 1916.

[18] The tabulated observations indicate a value of over 0.66, however.

velocity of the balloon through the air. Further, the final temperature reached by any body in the air will be that of the air, if all outside radiation is removed, and therefore the rise in temperature of a balloon fabric in sunlight above that of the air is a direct indication of its effect in varying the buoyancy of the balloon. For this reason it must not be supposed that the radiation properties become of less importance at high altitudes, where the air temperature is much lower than at the ground. The true temperature of a balloon will decrease as it ascends, owing to the increasing rate of loss of heat to the cooler air, but the increasing solar intensity will tend to raise its temperature to reach radiation equilibrium. If the effective wind velocity is not changed, the result will be a greater difference in temperature, between the upper surface of the balloon and the air, at a high altitude than at a low altitude.

3. EXPERIMENTAL MEASUREMENTS WITH MODEL BALLOON

It would prove interesting to make actual temperature measurements on airships in flight, for although several attempts have been made by others, notably by Bassus and Schmauss,[19] there are practically no data of much value available as yet, since these authors and later Stern,[20] and also Emden,[21] in discussing the transmission and absorption of balloon fabrics, make the erroneous assumption that the temperature for radiation equilibrium is the same for all surfaces, namely, that of a black body. They arrive at the astonishing conclusion that the equilibrium temperature would be the same for both a perfectly black balloon fabric and an aluminum-coated fabric and that the only difference in their behavior toward sunlight is that the aluminum-coated fabric requires a longer time to reach equilibrium and hence remains cooler longer. They fall into this error, apparently, by neglecting to consider that surfaces, other than those of "black" or "gray" bodies, do not have a uniform absorption throughout the spectrum. Thus, the absorption of a surface for sunlight can not be used in the formula for total radiation, equation 5, in solving for the equilibrium temperature of the surface, for in deriving this equation the absorption in the region of reradiated energy is used. They make no distinction between the absorption in these two widely separated spectral regions, using these values interchange-

[19] Zs. f. Flugtechnik, 2, pp. 216, 295, 1911; 3, p. 258, 1912; 4, p. 297, 1913; 5, p. 79, 1914.
[20] Zs. f. Flugtechnik, 6, p. 145; 1915.
[21] Zs. f. Flugtechnik, 3, p. 315; 1912.

ably. As a result, all of their temperature measurements were made for the contained gas in place of the controlling factor, the fabric.

In the present investigation it was not found possible to make measurements on balloons under service conditions. Accordingly it was decided to make a preliminary survey of the problem by means of measurements on a small-sized model balloon. These measurements were designed to show the temperature of the surface of the balloon at different points and the temperature gradient in the gas contained in the envelope. Furthermore, experiments were made to show the relative temperature rise, above that of the air, of typical fabrics when exposed to sunlight.

(*a*) *Description of Apparatus.*—The model balloon which was used for the measurements of the temperatures of the fabric and gas was kindly loaned by the Goodyear Tire & Rubber Co. It was a model of a stream-line dirigible and had a maximum diameter of 3 feet and a length of 12 feet. The measurements of temperature were made by means of copper-constantan thermocouples and a potentiometer. The couples were made by soldering the elements in the form of No. 36 B. & S. gage wire, to very thin, bright metal receivers, 1.5 mm by 3.0 mm.[22] Some of these receivers were in turn cemented to the inner surface of the balloon by means of Canada balsam. In this way an excellent contact was made between the thermocouple and the fabric and yet the receiver was not so massive as to affect the temperature measurements. Similar thermocouples of the same size were supported at various points inside the balloon by means of the No. 36 wire leads. These could be drawn from one side of the balloon to the other, thus exploring the temperature of the gas throughout a circular cross section of the balloon.

In order to determine the relative rise in temperature of different fabrics, square samples 7 cm on a side were supported in a position for normal solar incidence with a thermocouple, as described above, mounted on the lower surface. Two fabrics were exposed at the same time, one being used as a standard and all others compared with this one. The temperature of a number of fabrics exposed to sunlight was measured in this way by Dr. Coblentz, with the assistance of Mr. W. B. Emerson, in 1917, and the results formed the basis of a preliminary report from the Bureau on the "Heating Effect of Sunlight upon Balloon Fabrics."

[22] The use of this form of thermocouple was suggested by Dr. Coblentz; their construction is described by him in the Bulletin of the Bureau, 9, p. 15, 1913.

In order to place results obtained at different times and under different conditions of solar radiation and air temperature on a comparable basis, we have assumed a standard condition where the air temperature is 25° C and the solar intensity equals 1.4 g calories per square centimeter per minute. Each measurement included observations of the true temperature of the fabric and the air, the temperature difference of the fabric and standard, standard and air, and the value of the rate of solar radiation during these measurements. The value under the standard conditions is calculated from these observations.

(*b*) *Sources of Error in Measurements.*—The thermocouples with leads and cables were checked at several points and found to agree within 0.1° C over the range of temperatures for which they were used. It could not be concluded, however, that the temperatures

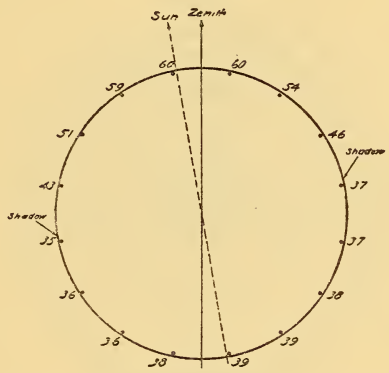

FIG. 3.—*Temperature distribution on envelope of model balloon*
Air temperature=23° C; solar intensity=1.33 g cal per cm² min.

of a surface or of the gas were measured with this accuracy. For this reason several couples were mounted both on the inside and outside of the upper surface of the model balloon. From measurements of the difference in temperature of these couples it was found that the absorption or emission of the tin receiver to which the thermocouple is soldered apparently has little effect in determining its temperature. It is concluded, therefore, that the true temperature of the surface is measured within 0.2° C. To check the accuracy in measuring the temperature of the gas, two of the above receivers were supported in the air, one in the shade and the other in direct sunlight. The one exposed to sunlight was from 0.1° to 0.5° C hotter than the one in the shade, but with the couple in the sunlight shaded by a sheet of balloon fabric, this difference was never greater than 0.2° C.

(*c*) *Experimental Results.*—The temperature of the surface of the balloon as found in one typical series of observations is shown in Fig. 3. In this figure the locations of the thermocouples are shown by black dots and the temperature of the fabric at each point is indicated by the figures. This distribution of temperatures is typical of the many observations made. It will be noted that the increase in temperature of any point on the upper surface above that of the surface just below the shadow line is found to vary approximately as the cosine of the angle between the sun's rays and the normal to the surface at that point. This indicates that, over the range of solar intensities experienced, the increase in temperature of the fabric is directly proportional to the intensity of the solar radiation. Fig. 4 shows the values of Fig. 3 plotted in

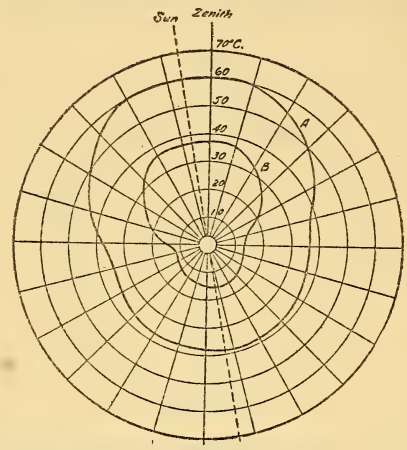

FIG. 4.—*Graph showing temperature of envelope and temperature difference between envelope and air at different points*

Air temperature=23° C; solar intensity=1.33 g cal per cm² min.

polar coordinates. Curve *A* is the true temperature, while curve *B* is the temperature difference between the balloon surface and surrounding air.

A significant fact to be noted in these curves is that the minimum temperature occurs just below the beginning of the shadow on each side of the balloon. This condition was found in every series of measurements made, and it can not be considered, therefore, unusual. The higher temperature at the lower surface is probably due to a greater intensity of transmitted sunlight at this point. The highest temperature measured on this model balloon was 66.4° C (152° F) with a surrounding air temperature of 25.5° C

(78° F) and a solar radiation intensity of about 1.42 g calories per square centimeter per minute.

Measurements of the temperature of the contained gas indicate practically a uniform temperature (within 1° or 2° C) throughout the lower half of the balloon, whereas the temperature varies in the upper half. The variation of the temperature in the interior of the balloon is shown in Fig. 5 by a series of isothermals spaced for equal differences in temperature. The heavy dots indicate the position of the thermocouples used, and the accompanying figures the observed temperatures in degrees. Because of the fact that 10 minutes are required for making this series of about 30 measurements, and that during this interval of time changes in the conditions affecting the temperature

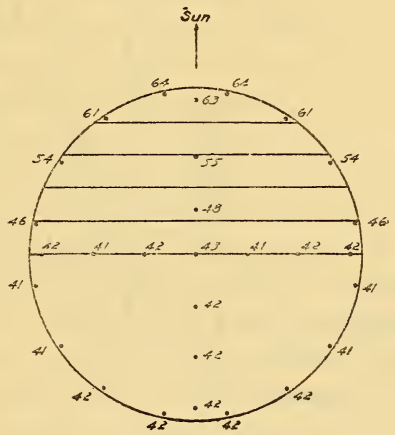

Fig. 5.—*Temperature distribution inside model balloon*

occur, it was necessary to combine the results of several series of measurements in order to find the condition at a given instant. As a check on this relative temperature distribution, a large number of measurements of temperature differences were made between different points on the surface of the balloon and in the gas. Fig. 5 indicates the combined result. It should be noted that a difference in temperature of as much as 25° C may exist in different parts of the gas. It is therefore important, in reporting such measurements to specify the location of the point at which the measurement is made. It is, of course, improbable that the temperature would vary in exactly the same manner throughout the envelope of a full-size balloon. In fact the model balloon differs from a full-size balloon in that it contains no air ballonets. The presence of the ballonets in the full-size

envelope would probably tend to accentuate the difference in temperature between the upper and lower surfaces. The ballonet acting as a sort of diaphragm across the interior of the balloon would absorb the transmitted and reradiated energy from the upper surface and heat the upper surface by reradiation just as did the lower surface in the model balloon. The lower surface would consequently be relatively cooler than in the case of the model balloon. The present measurements, however, indicate to a certain extent the character and magnitude of the temperature difference which may be expected.

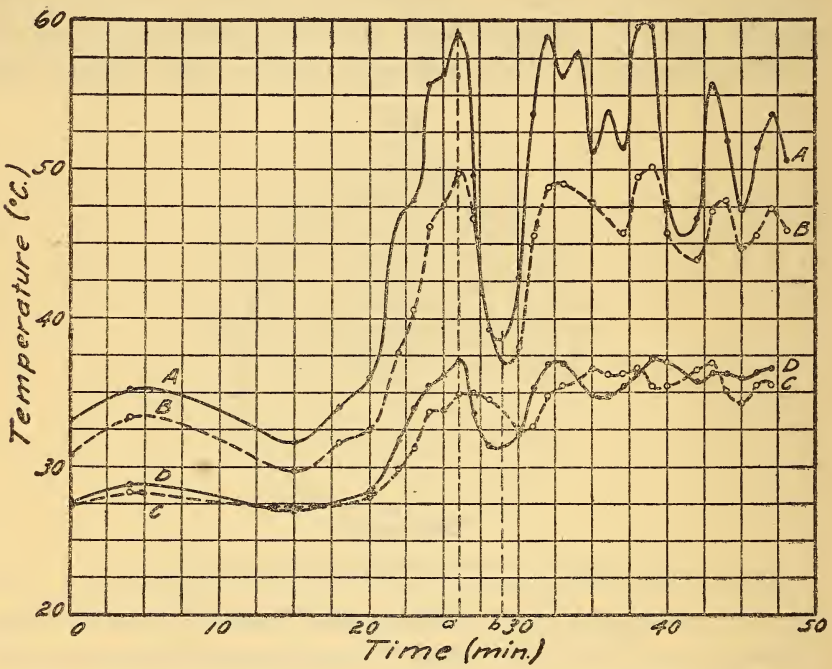

Fig. 6.—*Variation of temperature of balloon with changing radiation intensity*

It is worth while, also, to note the rapidity with which the temperature changes at different points in a balloon when passing from direct sunlight into the shadow of a cloud, and vice versa. For this purpose measurements of the temperature of the upper and lower surfaces, and the temperature of the gas at the center and half way between the center and upper surface, were made as nearly simultaneously as possible. These measurements were made on the model balloon at a time when small dense clouds were visible. The results are shown graphically in Fig. 6. The ordinates represent the true observed temperature and the abscissas the time interval in minutes. The curves

A, *B*, *C*, and *D* represent, respectively, the temperature of the upper surface, of the gas midway between the center and the top, of the gas at the center, and the temperature of the lower surface.

From the two lower curves it will be noticed that under a more or less steady condition gas at the center is receiving enough heat from the upper surface to raise its temperature a fraction of a degree above that of the lower surface. With rapidly changing temperature, however, the temperature of the gas at the center is seen to be almost wholly dependent on that of the lower surface and to lag behind it from 1 to 2 minutes.

During the time interval (*a–b*) of 3 minutes the temperature changes were as follows:

	C°
Upper surface	20.6
Upper gas	13.0
Center gas	1.5
Lower surface	5.8

If the "upper" gas temperature represents an average for the upper half of the balloon and a mean of the center gas and lower surface temperatures an average for the lower half, then the average temperature change of the gas is 8.4° C. The initial temperature was 43° C or 316° absolute; therefore, the volume diminished 2.7 per cent (8.4/316) in 3 minutes, the pressure remaining constant. This means a volume, or buoyancy, change of 0.9 per cent per minute. To show the effect of such a rapid change it may be supposed (though not probable) that the average temperature of the gas in an airship of 200 000 cubic feet capacity suffers such a change. In such a case it would be necessary to fill the ballonet at the rate of 1800 cubic feet per minute to keep the envelope properly inflated. It would be interesting to observe the actual magnitudes of these changes in practice.

(*d*) *Relative Temperature Rise of Fabrics.*—The rise in temperature must be measured for all fabrics under identical conditions, if a fair comparison is to be secured. It was found that the increase in temperature above that of the surrounding air was directly proportional to the solar intensity over a rather wide range. It was therefore possible to make the temperature measurements for various solar intensities and extrapolate for a standard solar intensity, which was taken as 1.4 g calories per square centimeter per minute. All results are given for still air surrounding the fabric at a temperature of 25° C, which is the temperature

at which permeability measurements of these fabrics are made in this laboratory.

The rise in temperature for a number of fabrics, when measured in this manner is shown in the last column of Table 1. It will be noticed that for all fabrics, except those which are aluminum coated, the absorption is a relative measure of the temperature rise. The diffuse reflecting power is an inverse measure of the relative temperature rise. The measurement on the fabric from the model balloon was made on the balloon and is, therefore, not comparable with the other values because the fabric was heated by reradiation from the lower surface. In the case of the aluminized fabrics, the reflecting power presumably remains high at wave lengths in the infra-red near 9μ, and according to Kirchhoff's law the emissivity, or radiating power, must be low. Therefore, the aluminized fabric would have to be raised to a higher temperature in order to radiate at a given rate, than would some other material with a higher emissivity in the infra-red near 9μ. The radiation properties of the several aluminized fabrics at, or near, this wave length must be nearly the same, for the relative temperature rise among fabrics of this type is proportional to the radiation absorbed.

This same reasoning indicates that all of the fabrics investigated, except those which are aluminum coated, have nearly identical radiation properties at, or near, a wave length of 9μ. It was for this reason that it was not considered worth while for the purpose of this work to investigate the actual radiation properties in the region of the infra-red.

4. SOME TEMPERATURE CALCULATIONS

The fabric of the upper surface of a balloon loses most of the heat appearing there toward the outside. In other words, only a small proportion of the total is carried to the inside and lost through the lower surface of the balloon. For calculating the maximum temperature due to sunlight, above which no balloon fabric could rise, a material may be considered which has a totally absorbing surface directed toward the sun and a totally reflecting surface directed away from the sun. Gas conduction and convection losses may become very small, and for the present purposes they may be considered zero, that is, we may assume that no gas is present.

In this hypothetical case the radiant energy absorbed and that reradiated by the totally absorbing surface will be equal to the solar intensity at this surface. And from the Stefan law of total radiation:

$$E_s = \sigma T^4 \tag{14}$$

or

$$T = \sqrt[4]{\frac{E_s}{\sigma}} \tag{15}$$

Values of T for solar intensities of 1.40 (at the earth's surface) and 1.67 (at an altitude of 5000 m) are given below:

E_s	T	t	
	°Abs.	°C	°F
1.40	362	89	174
1.67	378	105	221

The number of factors involved and the number of assumptions which must be made in any specific case make the application of the radiation equations to practical problems rather difficult. They have a certain value, however, in showing the relative magnitude of changes which may be expected and provide a rough check on experimental data. By means of these relations we have estimated the relative quantity of heat lost by radiation from the upper surface of the model balloon and that lost by convection to the atmosphere when the balloon was in still air at 26° C and the temperature of the upper surface of the balloon was 65° C. Under these conditions approximately 80 per cent of the heat loss may be due to radiation, a fact which emphasizes the relative importance of the radiation properties of a fabric in determining its temperature in sunlight. The convection loss calculated from Langmuir's [23] equation also indicated that approximately 80 per cent of the heat loss was due to radiation.

The above calculations assume the air movement to be small, that is, there is a negligible wind velocity or velocity of the balloon through the air. With a high wind velocity the loss of heat by convection may become larger than that by radiation. It is useless to compute the resulting temperature for various velocities, but it should be pointed out that increasing wind velocity causes the temperature of the balloon to approach that of the air as a limit. It is desirable, therefore, that the temperature rise of the balloon above that of still air be small, so that rapid changes of

[23] Phy. Rev., 34, p. 401; 1912.

wind velocity or the velocity of the balloon through the air, may cause a relatively small change of the buoyancy of the balloon.

VI. DETERIORATION OF FABRIC CAUSED BY RADIATION

It has long been known that light is one of the chief agents causing the deterioration of balloon fabrics. Both the cotton cloth and the rubber are injured by exposure to light, the extent of the damage being determined by the character and intensity of the light as well as the duration of the exposure. Aside from the strictly photochemical reactions produced by light, the rubber in particular is injured by the relatively high temperatures to which it may be raised by exposure to radiation.

Because of their well-known photochemical activity, the ultra-violet rays have been considered the chief factors in the deterioration caused by light. Edwards and Moore [24] in some tests on the use of ultra-violet light for determining the lasting qualities of fabrics were able to show that exposure to equal quantities, though of different spectral distribution, of ultra-violet radiation (wave lengths less than 0.45μ) from the sun and also from a mercury vapor arc in quartz, produced different degrees of deterioration depending on the fabric which was being tested. Nevertheless, the action was qualitatively the same with both sources of light. Further discussion of the relation between the character of the radiation and the rate of deterioration must await the completion of more extensive tests.

The effect of heat in producing the deterioration of fabric has been discussed by Edwards [25] and Tuttle [25]. Although maintaining the fabric at a temperature of 70° C in an electrically-heated air bath produced rapid deterioration, the action was characteristically different from that caused by exposure to light. One fabric in particular that deteriorated extremely rapidly on exposure to the weather and in service, remained flexible and was damaged least by the heat test. Another fabric which showed very good lasting qualities on exposure to weather and in service, became stiff and deteriorated rapidly when heated.

It is impossible at the present time to distinguish between the photochemical action on the fabric caused primarily by the absorbed radiation and the action caused by the heat resulting from the absorption of radiation. There are very good reasons, however, for assigning the major role to light. Accordingly, the most

[24] Fourth Ann. Rep. Nat. Advisory Comm. Aeron. (to appear in 1919).
[25] Third Ann. Rep. Nat. Advisory Comm. Aeron., pp. 459 and 463; 1918.

durable fabric considered from this standpoint is the one which has the best protection against light, and which also shows the least increase in temperature when exposed to sunlight. These points will be considered more at length in the succeeding section on the selection of fabric.

A further effect produced by the heating of the fabric is its increase in permeability. The permeability of rubber to hydrogen increases about 4 per cent for an increase in temperature of 1° C at about 25°. In the case of the model balloon (see Fig. 4) where the upper surface was at a temperature of 60° C, the permeability of the fabric was about 3 times as great as at 25° C, which is the standard temperature for testing fabric for permeability. Although a fair proportion of the loss of gas from a balloon occurs through the seams, nevertheless, the increased loss of gas through the fabric at such high temperatures is worthy of attention.

VII. SELECTION OF FABRIC

There are so many qualities which may be desirable in a balloon fabric and the requirements for each may be so conflicting that the resultant choice must be a compromise. The choice will, however, take into consideration the specific use for which the fabric is intended. The considerations of strength and elastic properties are more or less independent of the other properties of the fabric. Weight, radiation characteristics, color, visibility, and durability are, however, all interrelated and must be considered together.

It has been pointed out that from the standpoint of the effect of radiation in raising the temperature, a nearly transparent fabric or a perfectly reflecting surface would be most desirable. Such a fabric is not a possibility at the present time, however. A fabric with a white rubber coating compounded with zinc oxide would also be favorable from this standpoint, although not from others. Fabrics Nos. 8 and 9 in Table 1, which have the color of the unbleached cloth and the pale yellow of pure vulcanized rubber, show a very small increase in temperature, but because they lack any protection against the injurious action of light their useful life would be very short. This objection, however, does not apply to the aluminum-coated fabrics. The aluminum coating not only protects the gas-retaining rubber film by virtue of its opacity to light, but also, because of its high reflecting power, remains comparatively cool when exposed to sunlight. The deterioration of fabrics 8 and 9 when exposed to the weather in

summer at Washington is about 10 times as rapid as in the case of the best aluminum-coated fabrics. The aluminum-coated fabric is, therefore, finding extensive use because of its superior durability. For military purposes where low visibility is desirable, there are sometimes objections to the use of the bright and highly reflecting aluminum coat. Also the weight of the aluminum coating may be undesirable for envelopes where a very light fabric is required. In these cases it is necessary to use a dyed or pigmented rubber-coated fabric which meets the color and visibility requirements and yet shows a minimum temperature effect and satisfactory durability characteristics.

In the case of a captive balloon the consideration of buoyancy changes would not be so important as with a free balloon or a dirigible balloon. Visibility and color, however, might be of more importance. The question of lasting qualities is almost always important.

It has been possible only to outline in these few paragraphs the many considerations which affect the choice of a balloon fabric. The effect of radiation upon the fabric should not be lost sight of in any case, even if it is not of most importance; frequently an improvement of the fabric in this respect can be obtained without the sacrifice of any other desirable characteristics.

VIII. SUMMARY

The object of this paper has been to describe briefly the effect of solar radiation upon balloons.

Preliminary to the subject proper a summary is given of the characteristics of solar radiation and atmospheric conditions which bear directly on the problem. The radiation characteristics of the fabrics themselves are then discussed. A series of measurements on typical balloon fabrics showed an absorbing power for radiation varying from 45 to 95 per cent. The fundamental relations governing the temperature of balloon fabrics when exposed to solar radiation are outlined and the application of these to the calculation of balloon temperatures discussed. Because of the multiplicity of factors involved, the calculation of such temperatures is of very limited value. However, by means of measurements on a model balloon, the magnitude and distribution of the temperatures involved in both gas and fabric are well illustrated. With the model balloon the temperature of the upper surface in bright sunlight was frequently over 60° C. The rise in tempera-

ture of different fabrics above that of the atmosphere when exposed to sunlight under certain definite conditions varied from 20° C to 39° C. The importance of the radiation factor in governing buoyancy changes, in causing increased permeability of the fabric to hydrogen, and in its effect on the life of the fabric has been emphasized. In the selection of a fabric for any specific purpose, the effect of radiation in its various phases should always be considered and given due weight.

The immediate application of all of the ideas developed here is, of course, not possible; they point the way to future progress. It seems fairly obvious that a thorough understanding of the effect of radiation upon balloons will be essential to their most rapid and scientific development, because solar radiation is so intimately connected with many phases of their design and operation.

WASHINGTON, January 21, 1919.