REPORT No. 310

PRESSURE ELEMENT OF CONSTANT LOGARITHMIC STIFFNESS FOR TEMPERATURE COMPENSATED ALTIMETER

By W. G. BROMBACHER and F. CORDERO
Bureau of Standards

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SUMMARY

The usual type of altimeter contains a pressure element, the deflections of which are approximately proportional to pressure changes. An evenly divided altitude scale is secured by using a mechanism between the pressure element and pointer which gives the required motion of the pointer. A temperature-compensated altimeter was constructed at the Bureau of Standards for the Bureau of Aeronautics of the Navy Department which contained a manually operated device for controlling the multiplication of the mechanism to the extent necessary for temperature compensation. The introduction of this device made it difficult to adjust the multiplying mechanism to fit an evenly divided altitude scale. To meet this difficulty a pressure element was designed and constructed which gave deflections which were proportional to altitude; that is, to the logarithm of the pressure. Mathematically, the logarithmic stiffness S' of the element equals

$$S' = \frac{d \log_e P}{dy}$$

from which is derived the deflection y for the change in pressure from P_o to P

$$y = \frac{\log_e P - \log_e P_o}{S'}$$

The element consisted of a metal bellows of the sylphon type coupled to an internal helical spring which was designed so as to have a variable number of active coils. This report presents a description of and laboratory data relating to the special pressure element for the altimeter. In addition equations which apply generally to springs and pressure elements of constant logarithmic stiffness are developed, including the deflection and the spacing between the coils in terms of the constants of the helical spring and pressure element.

INTRODUCTION

An altimeter is a pressure-measuring instrument calibrated in altitude according to the altitude-pressure relation of a standard atmosphere. It consists essentially of two parts, one the pressure element and the other the multiplying mechanism. The latter is that part which connects the pressure element to the pointer. As pressure elements ordinarily have deflections very nearly directly porportional to pressure changes, a scale evenly divided in altitude units requires that the ratio of the linear motion of the pointer to the deflection of the pressure element (multiplying ratio) must vary continuously with the air pressure.

In the course of the development of a temperature-compensated altimeter for the Bureau of Aeronautics of the Navy Department considerable difficulty was experienced in obtaining an evenly divided altitude scale. This was largely due to the restrictions imposed on the multiplying mechanism by the device by which compensation was made for the effect of air temperature, which was secured by suitably controlling the multiplication of the motion of the pressure element. This was manually controlled by a thumb nut by which settings were made to correspond to the observed air temperature at the ground level. The addition of this extra mechanism to the altimeter did not appear to permit the adjustment necessary for an evenly divided scale. It was not considered advisable to change the general design of the mechanism.

Consideration was then given to the possibility of designing a pressure element which would give deflections proportional to changes in altitude (that is, proportional to the logarithm of the pressure) and thus eliminate the need for a mechanism with a variable multiplying ratio. The original pressure-element design consisted of a "sylphon" bellows enclosing a steel helical spring and evacuated in accordance with usual practice. The possibilities narrowed down finally to the modification of the design of the spring. A successful design was finally found which gave approximately the desired straight-line relation between deflection and altitude in the altitude range of the altimeter.

STATEMENT OF THE PROBLEM

The relation between pressure and altitude to which altimeters are calibrated in the United States is that of the standard atmosphere which is for altitudes below 35,332 feet,

$$Z=63{,}691.8\ \frac{T_m}{288}\log_{10}\frac{760}{p} \tag{1}$$

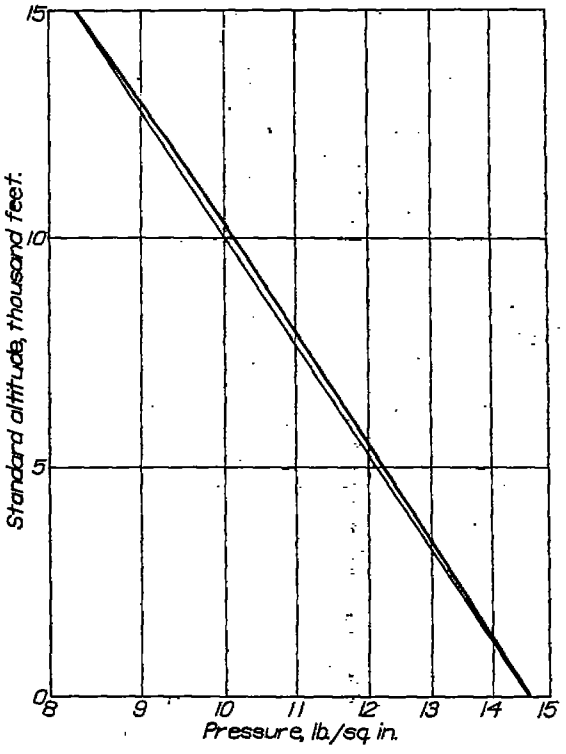

FIGURE 1.—Standard altitude varies approximately as the logarithm of the air pressure

in which Z is the standard altitude in feet, T_m the standard mean temperature for Z, and p the air pressure at altitude Z in millimeters of mercury. (For further details on the standard atmosphere see References 1, 2, and 3. For convenient altitude-pressure tables, see Reference 3.) An inspection of equation (1) will show that variations in the temperature term $T_m/288$ are of the second order compared with those of $\log\frac{760}{p}$. This point is brought out in Figure 1, in which standard altitude is plotted against the logarithm of the pressure. The deviation of the curve from a straight line is so small that for all practical purposes a pressure element with deflections proportional to altitude is secured if the deflections are proportional to the logarithm of the pressure.

The solution depends entirely on the design of the spring. This was accomplished by adjusting the spacing between the coils so that the number of active coils of the spring gave the desired stiffness. Thus, if the pressure acting externally on a pressure element containing such a spring increased, the number of active coils decreased and vice versa. The inactive coils, being in contact, could not contribute to the deflection.

It is necessary for the purpose of design to obtain a relation between the spacing between the coils of the spring of a "logarithmic pressure element" and the position on the spring. The latter may be best located by giving the distance on the spring wire starting from the bottom of the spring. The following assumptions are fundamental:

1. The unmodified pressure element gives a straight line relation between pressure and deflection for the working pressure range.
2. A helical spring is used.
3. The relation between spring stiffness s and length of active wire l is

$$s=\frac{1}{Kl}$$

where K is a constant.

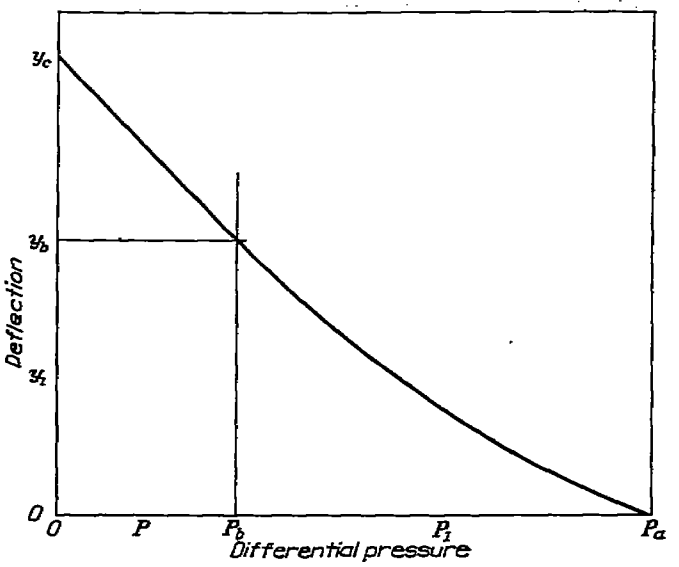

FIGURE 2.—Typical curve for logarithmic element
$y_1 \propto \log P_1$, $y_b \propto P$

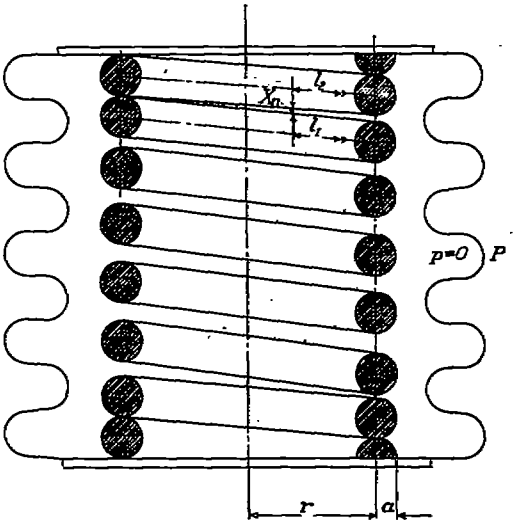

FIGURE 3.—Cross section of pressure element

DESIGN OF SPRING FOR LOGARITHMIC PRESSURE ELEMENT

DEFINITIONS

P = the differential air pressure in pounds per square inch acting on the pressure element.

P_a refers to the value at sea level atmospheric pressure;

P_b to the value below which all of the spring wire will contribute to the deflection;

P_1 to the value in the region P_a to P_b;

P_0 to zero differential pressure.

See Figures 2 and 3.

S = the stiffness of the pressure element in pounds per inch corresponding to values of the pressure P.

y = the deflection of the pressure element in inches corresponding to values of the pressure P.

S' = the logarithmic stiffness of the pressure element.

s = the stiffness of the spring in pounds per inch; the various values correspond to the pressure P.

l = the length of the active portion of the spring wire in inches; the various values correspond to the pressure P. l is measured from the bottom of the spring to the top. It forms a convenient way of locating points on the spring; thus $l=0$ is the bottom of the spring, $l=l_b$ is top, and $l=l_1$ is the length of spring wire which is active when the pressure element is subject to pressure P_1, and marks the point on the spring below which the spring wire is active, and above which, inactive.

The corresponding values of the various quantities are given in the following table:

P	S	y	s	l
P_a	S_a	0	s_a	l_a
P_1	S_1	y_1	s_1	l_1
P_b	S_b	y_b	s_b	l_b
0	S_b	y_c	s_b	l_b

s_d = the stiffness of the sylphon in pounds per inch.

p = the gas pressure inside of the pressure element. This is zero. See Figure 3.

A_e = the equivalent area of the sylphon in square inches.

d_1 and d_2 = the diameter in inches, respectively, of the circumscribing and inscribing cylinders of the sylphon bellows.

r = the radius of the spring coils in inches.

a = the radius of the spring wire in inches.

G = the modulus in torsion of the spring material in pounds per square inch.

X_m = the sum of the spacings between all of the coils of the spring in inches between points l_b and l_1, measured on a generatrix of the cylinder passing through the center line of the wire. The spacing is that when the pressure element is subject to the differential pressure P_b.

X_m' = the same as X_m except that it refers to the value of X_m between points on the spring $l_2 = l_1 + 2\pi r$ and l_b.

X_n = the spacing in inches between two adjacent coils measured between points on the spring l_1 and l_2. See Figures 3 and 4. It equals $X_m - X_m'$ and therefore is the value when the pressure element is subject to a differential pressure P_b.

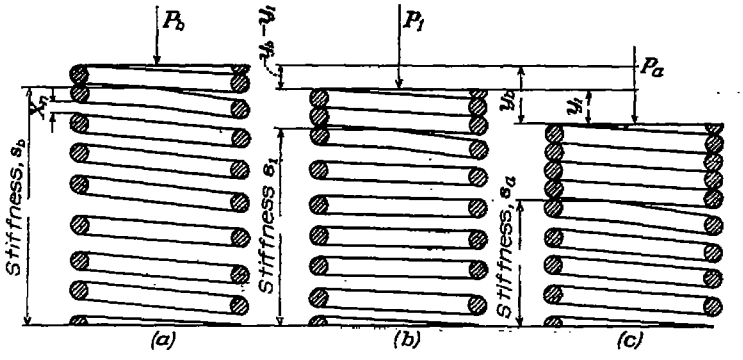

FIGURE 4

THEORY.—The stiffness of a pressure element is the sum of stiffnesses of the elements. (Reference 5.)

$$S = s + s_d \tag{2}$$

The stiffness of the sylphon or diaphragm capsule s_d is usually small in comparison to that of the spring.

The commonly used helical spring formulas given for s:

$$s = \frac{1}{Kl} \tag{3}$$

in which

$$K = \frac{2r^2}{\pi G a^4} \tag{4}$$

In order to meet the conditions, the deflection of the pressure element should be proportional to the standard altitude which, as shown in Figure 1, is very closely proportional to the logarithm of the pressure in the altitude range, 0 to 15,000 feet. That is,

$$\frac{\mathrm{d}\log_e A_e P_1}{\mathrm{d}y_1} = \text{a constant} \equiv S' \tag{5}$$

in which A_e equals for a sylphon,

$$A_e = \frac{\pi}{8}(\mathrm{d}_1^2 + \mathrm{d}_2^2) \quad \text{(Reference 4).} \tag{6}$$

Further,

$$S' = \frac{1}{P_1}\frac{\mathrm{d}P_1}{\mathrm{d}y_1} \tag{7}$$

and by the definition of stiffness,

$$S_1 = \frac{\mathrm{d}A_e P_1}{\mathrm{d}y_1} = A_e \frac{\mathrm{d}P_1}{\mathrm{d}y_1} \tag{8}$$

From equations (2), (7), and (8), adding the proper subscripts,

$$\begin{aligned} S_1 &= S' A_e P_1 \\ &= s_1 + s_d \end{aligned} \tag{9}$$

Substituting for s from equation (3) and evaluating for P_1

$$P_1 = \frac{1 + s_d K l_1}{S' A_e K l_1} \tag{10}$$

This gives the relation between l_1 and the pressure P_1.

In the region P_1 to P_a, it follows directly from equation (5), that

$$y_1 = \frac{\log_e P_a - \log_e P_1}{S'} \tag{11}$$

Noting equations (2) and (9) it follows that

$$s_1 = S_1 - s_d = A_e S' P_1 - s_d \tag{12}$$

The deflection, $y_c - y_b$ is

$$y_c - y_b = \frac{A_e P_b}{s_b + s_d} \tag{13}$$

s_b is here a constant, that for the spring when all of its length is acting.

It is desired to find a relation between the length of the spring wire and the gap or spacing between the coils.

Let the reference point be chosen at the condition when the pressure equals P_b, that is, the evacuated pressure element is subjected to the external pressure at which all the coils of the spring are active, but start to go out of action as the pressure is increased. See Figure 4. As the pressure is increased to a given value P_1, the resulting deflection may be divided into two parts, that due to the part of the spring active at P_1, and that due to the part of the spring which has gone out of action in the pressure interval P_b to P_1. Let the component of the deflection of the element due to the coils which are active at pressure P_1, that is from $l=0$ to l_1 be designated by y_1'. The other component is X_m. Then

$$y_b - y_1 = y_1' + X_m \tag{14}$$

The component y_1' is

$$y_1' = \frac{A_e(P_1 - P_b)}{s_1 + s_d} \tag{15}$$

The above expression for y_1' is derived as follows: In Figure 4(b) the pressure element is subject to pressure P_1 and the spring has an instantaneous stiffness s_1 and a definite active portion

of length l_1. Referring now to Figure 4(a), if only the deflection of the portion of the spring l_1 that is y_1', be considered for the pressure change P_b to P_1, it is seen that the stiffness of the spring is constant and equal to s_1. The expression for y_1' then follows from the definition of stiffness, noting that the stiffness of the element is s_1+s_d.

The value of X_m is determined introducing the value of y_1 given in equation (11).

$$X_m=y_1-y_1'-y_b=-\frac{\log_e P_1-\log_e P_a}{S'}-\frac{A_g(P_1-P_b)}{s_1+s_d}-y_b \tag{16}$$

Substitute in equation (16) for P_1, the value given in equation (10) and for $\frac{A_g}{s_1+s_d}$ from equation (9).

$$X_m=\frac{1}{S'}\log_e\frac{l_a(1+s_dK\,l_1)}{l_1(1+s_dK\,l_a)}-\left[\frac{1}{S'}-\frac{l_1(1+s_dK\,l_b)}{S'\,l_b(1+s_dK\,l_1)}\right]-y_b \tag{17}$$

Let l_2 be defined by $l_2-l_1=2\pi r$. (18)

Then if l_2 be substituted for l_1 in equation (17) there is obtained

$$X_m'=\frac{1}{S'}\left[\log_e\frac{l_a(1+s_dK\,l_2)}{l_2(1+s_dK\,l_a)}\right]-\left[\frac{1}{S'}-\frac{l_2(1+s_dK\,l_b)}{l_bS'(1+s_dK\,l_2)}\right]-y_b \tag{19}$$

It is evident that the difference X_m-X_m' gives the spacing between adjacent coils of the spring in terms of the length of the spring wire. That is

$$X_n=X_m-X_m' \tag{20}$$

It should be noted that l, the length of the wire is always the length of the active wire. The convention is here conveniently adopted of measuring the wire length from the bottom of the spring to the top, the coils at the top going out of action as the pressure increases.

Equation (20) applies to pressure elements containing a diaphragm or sylphon and a helical spring and is based on the following assumptions:

(*a*) The sylphon or diaphragm gives a straight line pressure-deflection curve.

(*b*) The deflection is zero when the external pressure is equal to the atmospheric pressure and is approximately zero inside of the pressure element.

(*c*) The deflection is positive when the external pressure decreases and is proportional to the logarithm of the pressure for all values in the range from atmospheric to P_b. See Figure 2.

DESIGN OF LOGARITHMIC HELICAL SPRING

In view of the relations just developed there is no difficulty in arriving at the design equation for a simple helical compression spring, the deflection of which is directly proportional to the logarithm of the load.

Let $L=$ the load in pounds applied to the spring.

L_o and L_m are respectively the lower and upper limits of the loads for which the deflection is logarithmic.

L_1 is a load between L_o and L_m.

$y=$ the deflection of the spring in inches.

$y_o=o$, y_m and y_1 correspond to the loads L_o L_m and L_1.

$l=$ the length of the spring wire in inches, the subscripts corresponding to those for L. l is measured from the bottom end of the spring.

$X_m=$ the sum of the spacing between all of the coils of the spring in inches from the end l_o of the spring wire to any point l_1, measured on an element of the cylinder passing through the center line of the wire. It refers to the spacing when the spring is subject to the load L_o.

$X_m'=$ the same as X_m except that it refers to the value of X_m between the points on the spring $l_2=l_1+2\pi r$ and the top end of the spring l_o.

$X_n=$ the spacing in inches between two adjacent coils measured between points on the spring l_1 and l_2. The value is that when the spring is subject to load L_o.

The expressions for the load-deflection characteristics of a "logarithmic" helical compression spring are given below. As for the pressure element,

$$\frac{d \log_e L_1}{dy_1} = \text{a constant} \equiv s' \tag{21}$$

from which

$$y_1 = \frac{1}{s'} \log_e \frac{L_1}{L_o} \tag{22}$$

The following relation is also true, in which $\frac{dL}{dy}$ may be called the instantaneous stiffness.

$$\frac{dL}{dy} = s \tag{23}$$

From relations (21) and (23)

$$s_1 = s' L_1 \tag{24}$$

Similarly as for the pressure element just considered, the sum of the spacing X_m between the coils along an element in the cylinder passing through the axis of the wire is given the difference between the total deflection y_1 and the deflection y_1' due to the coils which remain active after load L_1 is applied. This may be made clearer by assuming that the spring is in two parts, one consisting of the portion of the spring, all the coils of which contribute to the deflection as the load changes from L_o to L_1 and the other of the portion which is fully active for load L_o and entirely inactive for load L_1. The deflection y_1 can be assumed as the sum of the deflections of the two parts. That is,

$$y_1 = X_m + y_1' \tag{25}$$

It is evident that

$$y_1' = \frac{L_1 - L_o}{s_1} \tag{26}$$

Putting in the values of y_1' given in equation (26) and y_1 from equation (22), equation (25) becomes

$$X_m = y_1 - y_1' = \frac{1}{s'} \log_e \frac{L_1}{L_o} - \frac{L_1 - L_o}{s_1} \tag{27}$$

Noting equations (3) and (24),

$$X_m = \frac{1}{s'} \log_e \frac{l_o}{l_1} - \frac{l_o - l_1}{s' l_o} \tag{28}$$

As before, choose l_2 so that

$$l_2 - l_1 = 2\pi r \tag{29}$$

and substituting l_2 for l_1 in equation (28), X_m' is obtained.

$$X_m' = \frac{1}{s'} \log_e \frac{l_o}{l_2} - \frac{l_o - l_2}{s' l_o} \tag{30}$$

The space X_n between any two coils is then given by

$$X_n = X_m - X_m' = \frac{1}{s'} \log_e \frac{l_2}{l_1} - \frac{l_2 - l_1}{s' l_o} \tag{31}$$

Equation (31) gives the desired relation between the spacing for adjacent coils and the length of the spring wire.

Equation (31) is identical with equation (20) for the pressure element if the stiffness of the sylphon s_s is assumed equal to zero.

DESCRIPTION AND PERFORMANCE OF "LOGARITHMIC" PRESSURE ELEMENTS

In connection with the development of the altimeter, four pressure elements were constructed according to the design which had been previously found to be satisfactory. It was found that the deflection-altitude curve of each element varied with the position of the gauge on the rigid top of the element due to slight tilting or cocking of the spring, which was caused by coils coming into or going out of action. The amount of this effect is shown in Figure 5, which gives deflection curves for four angular positions of the measuring gauge on the top of a pressure element. In each case the angular position at the proper distance from the center was found at which the deflection was most nearly proportional to the standard altitude or the logarithm of the pressure.

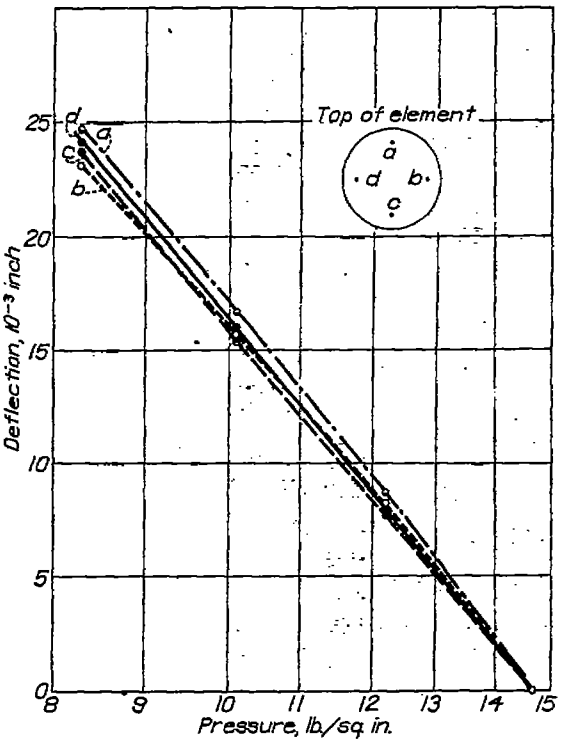

FIGURE 5.—Effect of position on the deflection of pressure element No. 4

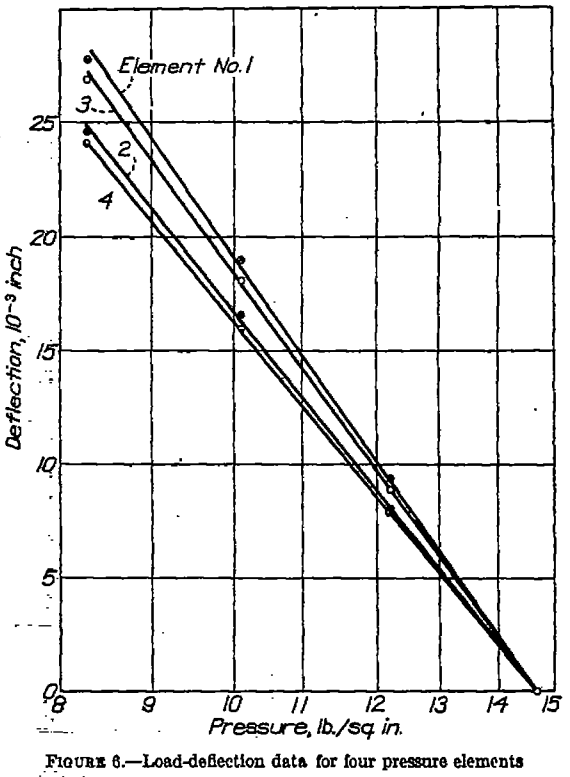

FIGURE 6.—Load-deflection data for four pressure elements

The best curves for the four elements are plotted in Figure 6. The variation in the maximum deflections is somewhat great but offers no difficulty, since the altimeter mechanism can be easily adjusted to give the proper deflection of the pointer. It is essential that the deflection curves be straight lines within close tolerances. The four elements when inserted in the altimeters were each found to give a satisfactory performance of the instrument. The range of the altimeter was 15,000 feet, which corresponds to pressure limits of 760 and 428.8 millimeters of mercury.

The helical springs were made from chrome-vanadium steel S. A. E. 6145 and were heat treated.

The constants of the spring and sylphon of element No. 3 are as follows, the symbols having the same meaning as in the previous sections.

S' logarithmic stiffness of element	20.9
r radius of coils in inches	0.405
a radius of wire in inches	0.062
G modulus in torsion in pounds per square inch	12×10^6
A_e equivalent area of sylphon in square inches	1.27
l_b total length of active wire of spring in inches	12.7
l_a length of active wire at differential pressure of 14.7 pounds per square inch in inches	4.86
P_a differential pressure in pounds per square inch (zero altitude)	14.7
P_b differential pressure in pounds per square inch (25,750 feet altitude)	5.28
s_d the stiffness of the sylphon in pounds per inch, approximately	5
s_a the stiffness of the spring in pounds per inch when the pressure is 14.7 pounds per square inch	385
s_b the stiffness of the spring in pounds per inch when all the wire is active	135
s_1 the stiffness of the spring in pounds per inch when the differential pressure is 8.29 pounds per square inch (15,000 feet)	215

The fundamental constant is the logarithmic stiffness S' defined in equation (5) which is obtained from Figure 6 by determining the slope of the deflection-log pressure line. Then in accordance with the relation

$$S_a = S' A_e P_a \tag{9}$$

the pressure element stiffness S_a was computed, from which the spring stiffness s_a was found by allowing for the sylphon stiffness. It is then possible to compute l_a.

It was assumed that the springs had five turns when all coils were active which, while reasonable, is open to question in view of the end effects which can not be easily calculated. Assuming still further that equation (9) holds in the region P_a to P_b, stiffness S_b was first calculated by use of equation (3) and then P_b determined by means of equation (9), noting that the pressure element stiffness equals the sum of that of the sylphon and spring.

The equivalent area A_e was computed by use of formula (6).

A measure of the differences in the four springs may be found in the variation of the value of S' determined from Figure 6.

Element No.	S'
1	20.0
2	23.0
3	20.9
4	23.6

The maximum fiber stress of the spring material occurs when the sylphon is evacuated and thus subject to a differential pressure equal to atmospheric. It was computed to be approximately 20,000 pounds per square inch.

The spacing between the coils of the helical spring which is required to give the above-described deflection curve will be calculated making use of the constants for element No. 3. As derived, the formulas relate to a spring in which the coils progressively go out of action from one end, while the spring was made so that the coils at each end go out of action as the load is applied. A modification of the latter method may offer the practical advantage of permitting an arrangement whereby the cocking can be eliminated. If the coils are spaced so that the two points of contact are kept 180° apart, no cocking should theoretically occur.

For the design of this pressure element formula (20) can be simplified with little loss in accuracy by neglecting the stiffness of the sylphon since it is small in comparison with that of the spring. The ratio of the two stiffnesses varies from 36 to 74 in the working pressure range. If $s_d = o$, formula (20) becomes

$$X_x = \frac{1}{S'} \log_e \frac{l_2}{l_1} - \frac{l_2 - l_1}{S' l_b} \tag{32}$$

The spacing X_x between adjacent coils of the spring were computed using the above simplified equation.

CALCULATION OF COIL SPACING

Coil between length of wire, l_2-l_1 inches		Spacing X_n in inches		
(l_1)	(l_2)	At differential pressure of 5.28 pounds per square inch (25,750 feet)	At differential pressure of 14.7 pounds per square inch (zero altitude)	At zero differential pressure
0	4.86	----------	All coils active.	----------
4.86	7.40	0.0106	0	0.0202
6.13	8.68	.0071	0	.0167
7.40	9.95	.0046	0	.0142
8.68	11.22	.0027	0	.0123
9.95	12.49	.0013	0	.0109
10.16	12.70	.0011	0	.0107
12.70	12.70	0	0	.0096

Computed deflection of element for pressure changes from—

	Inch
0 to 5.28 pounds per square inch	0.0479
5.28 to 14.7 pounds per square inch	.0473
0 to 14.7 pounds per square inch	.0952

The spacing of the constructed spring was such that the active portion of spring changed throughout the pressure interval 0 to 14.7 pounds per square inch, however no effort was made to obtain the logarithmic stiffness outside of the pressure interval 14.7 to 8.30 pounds per square inch. The total deflection for element No. 3 for the pressure change from 0 to 14.7 pounds

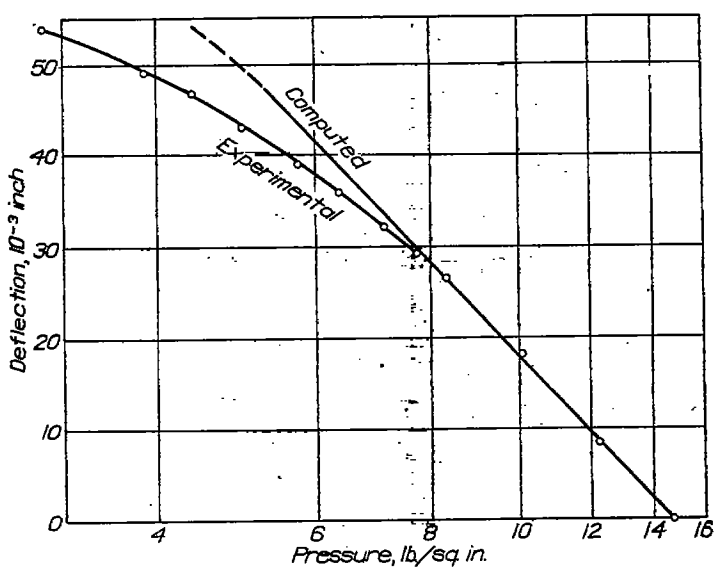

FIGURE 7.—Load-deflection data for element No. 3

per square inch is 0.079 inch, which compares with 0.094 inch given in the previous table. A comparison of the computed and measured deflections is given in Figure 7, which, of course, is significant only for pressures below 8.3 pounds per square inch, since the computation is based on the measured value of S', the logarithmic stiffness. The difference in the deflection for pressures below 8.3 pounds per square inch is not important, since it is easily accounted for by the difference in the spring as constructed and as assumed for computation. The constructed spring should have the greater stiffness under a given load because part of the coils are always out of action.

A measure of the smoothness of the deflection of the pressure element is given in Figure 8. The corrections to be applied to the altimeter readings are plotted against its readings. It will be noticed that the curves have a discontinuity at a reading in the region 5,000 to 7,000 feet (pressures, 12.2 to 11.4 pounds per square inch) which amounts to approximately 250 feet, or 1.6 per cent of 15,000 feet, and is approximately equivalent to a deflection of 0.0005 inch

of the pressure element. It is probably due to an irregularity in the spacing between the coils or to lack of smoothness in the surface of the spring wire. An idea of the elastic hysteresis of the pressure element is also given in Figure 8. This is the difference in the correction at the same reading for pressures decreasing and increasing. The maximum value for the instrument is about 90 feet, or 0.6 per cent of the maximum range, and is no doubt materially lower for the pressure element. There is remarkably little difference in the corrections for instrument temperatures of +25° and −30° C.

The authors desire to acknowledge the interest and encouragement of Lieut. M. F. Schoeffel, United States Navy, during the progress of the work.

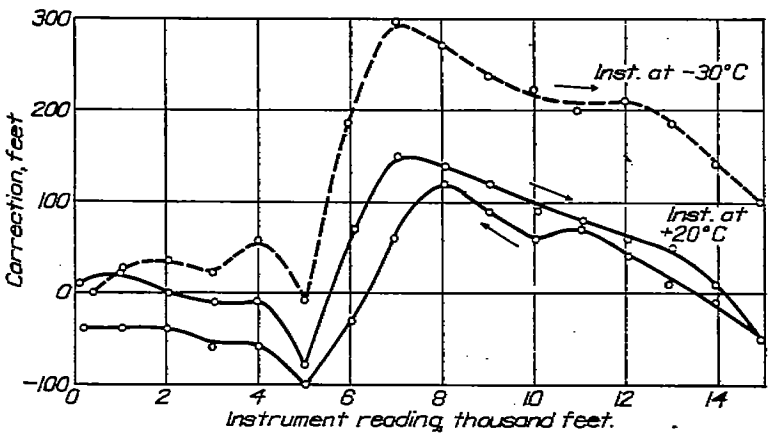

FIGURE 8.—Scale correction of BS-Navy altimeter, corrected for air temperature. (Temperature scale set at +13° C.)

CONCLUSION

The possibility of constructing a pressure element for altimeters which will eliminate the necessity for a variable multiplying ratio in order to obtain an evenly divided altitude scale has been demonstrated. Four such pressure elements were constructed. It was found possible to use any of the elements in the altimeter without making more than a routine and simple adjustment in the multiplying mechanism. The smoothness of operation of the pressure elements of logarithmic stiffness requires some improvement. This improvement can be obtained by more experience in the selection of the spacers used for securing the variable pitch of the springs and by investigating in greater detail the effect of surface irregularities in the spring wire due to heat treatment.

Roughly, the required multiplication of the deflection of a pressure element at 20,000 feet is twice, and at 40,000 feet four times that at sea level. It is evident that the difficulty of securing an evenly divided altitude scale increases with the range of altimeters. For high-range instruments of the ordinary type it might be practical to use the logarithmic pressure element and thus eliminate the necessity of adjusting the multiplying mechanism in order to obtain proper motion of the pointer.

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