IV. *On the Propagation of Sound in the Free Atmosphere and the Acoustic Efficiency of Fog-Signal Machinery: An Account of Experiments Carried Out at Father Point, Quebec, September*, 1913.

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[PLATE 1.]

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Part I.—ON THE MATHEMATICAL THEORY OF THE PROPAGATION OF SOUND IN A HOMOGENEOUS ATMOSPHERE WITH SPECIAL REFERENCE TO WAVES OF LARGE AMPLITUDE.

§ 1. Introduction.

The theory of the propagation of sound-waves of small amplitude such as are produced by ordinary acoustic instruments has received repeated experimental verification on almost every point. Over such distances as are available for indoor experiments, the atmosphere may be regarded as a homogeneous medium of constant temperature. The variations of pressure in such sound-waves are so small that the medium may be considered as a perfectly elastic fluid for which the relation between pressure and volume (per unit mass) is expressed by the adiabatic law

$$pv^{\gamma} = \text{const.} \quad \text{or} \quad p/p_0 = (\rho/\rho_0)^{\gamma} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where p_0 and ρ_0 refer to the pressure and density at standard temperature and pressure. It has long ago been verified by experiment that in the extremely rapid compressions and rarefactions which constitute sound-waves, equalization of the resulting inequalities of temperature by thermal conduction cannot take place with sufficient rapidity to bring about uniformity of temperature: the compressions and rarefactions may therefore be considered to take place under conditions of no heat-transfer, that is, under *adiabatic* conditions. γ is a constant which for air has the value $\gamma = 1{\cdot}414$. It was first pointed out by LAPLACE that under these conditions the Newtonian formula for the velocity of sound, $\sqrt{(p_0/\rho_0)}$, should be modified to

$$a = \sqrt{(\gamma p_0/\rho_0)}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Applying the above formula to the propagation of sound in air at standard pressure and temperature, and inserting $p_0 = 1{\cdot}013 \times 10^6$ dynes/cm.^{2}, $\rho_0 = 1{\cdot}293 \times 10^{-3}$ gr./cm.^{3}, we obtain for the calculated velocity of sound the value $a = 332$ metres/sec. $= 1089$ feet/sec., in good agreement with observation.

§ 2. PLANE WAVES OF SMALL AMPLITUDE.

For convenience of reference we write down several formulæ relating to the quantities employed to specify the state of motion in a plane sound-wave. Following RAYLEIGH'S* notation, we denote the velocity-potential at a time t and distance x in the direction of propagation of a harmonic train of waves by

$$\phi = \mathrm{A} \cos 2\pi\,(x-at)/\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where A is a constant depending on the amplitude and λ is the wave-length. If n be the frequency, we have the fundamental relation of wave-motion

$$a = n\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

If $[d\mathrm{W}/dt]$ represent the average rate of propagation of energy across unit area of the wave-front it is shown that

$$[d\mathrm{W}/dt] = 2\pi^2\mathrm{A}^2\rho_0 n^2/a, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

while the maximum pressure variation or pressure amplitude $|\delta p|$ is given by

$$|\delta p| = 2\pi\rho_0 \mathrm{A} n. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

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* RAYLEIGH, 'Theory of Sound,' vol. II., p. 15 (1896).

Hence expressing the rate of propagation of energy in terms of the pressure amplitude we have

$$|\delta p|^2 = 2a\rho_0 [d\text{W}/dt]. \qquad (7)$$

It is convenient to specify the state of affairs in the medium at any instant by the *condensation* s defined by the equations

$$s = \delta\rho/\rho_0 = (1/\gamma)\, \delta p/p_0. \qquad (8)$$

The displacement amplitude in the medium $|\xi|$ is given by the formulæ

$$|\xi| = \text{A}/a = |\delta p|/(2\pi n a\rho_0) = a|s|/(2\pi n), \qquad (9)$$

and the velocity displacement by

$$|\dot{\xi}| = 2\pi\text{A}/\lambda = |\delta p|/(a\rho_0) = a|s|. \qquad (10)$$

One of the most important results arising from the fact that waves of small amplitude are propagated with a constant velocity independent of their intensity is the application of the principle of superposition of vibrations. By the use of FOURIER'S Theorem it is proved that a periodic disturbance of any wave form may be analysed into a number of simple harmonic waves whose sum gives rise to the complex disturbance considered. It is thus sufficient in the case of sound-waves of ordinary intensity to consider the propagation of a simple wave, as discussed in equations (3) to (10). The relative harmonic constituents of the complex wave preserve their relative amplitudes unaltered during propagation; in other words, the *quality* of the sound is propagated to a distance without change. This fact is well illustrated by the everyday experience that the various notes from a number of musical instruments played simultaneously can be individually recognized over long distances. These points are emphasized because, as will be seen later, they no longer remain true in the case of waves of very great amplitude such as those emitted by a powerful fog siren.

It may be mentioned in passing that sound-waves of ordinary intensity are propagated with extremely little dissipation of energy due to viscosity or heat-conduction, the calculations having been carried out by STOKES* as long ago as 1845; here again the circumstances are different in the case of very intense waves, the experiments to be discussed in the sequel indicating that sound-waves of sufficient power to be audible at great distances can only be generated at the expense of heavy atmospheric losses, especially in the immediate neighbourhood of the generator.

§ 3. SPHERICAL WAVES OF SMALL AMPLITUDE.

An important practical case of propagation of sound is that of waves emanating from a concentrated source. As in the case of plane waves we assume for simplicity

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* STOKES, 'Cambridge Transactions,' vol. VIII., p. 287, 1845. See RAYLEIGH'S 'Sound,' vol. II. p. 315 (1898).

a simple harmonic type, small amplitude and negligible atmospheric losses. If we suppose the waves to be confined in a conical surface of solid angle ω, the velocity potential which determines the motion at a distance r from the source is

$$\phi = (\mathrm{A}/\omega r) \cos \kappa\,(at-r) \qquad (11)$$

If λ is the wave-length and n the frequency we have

$$\kappa = 2\pi/\lambda \text{ and } n = \kappa a/(2\pi) \qquad (12)$$

The rate of introduction of air at the source is A $\cos \kappa at$, and it is easily proved* that the pressure amplitude is given by

$$|\delta p| = \rho_0 |\partial\phi/\partial t| = \rho_0 \kappa a \mathrm{A}/(\omega r) \qquad (13)$$

If the source be situated close to a rigid plane, we have $\omega = 2\pi$, and obtain

$$|\delta p| = \rho_0 n\mathrm{A}/r \text{ and } a|s| = n\mathrm{A}/(ar) \qquad (14)$$

The total rate of emission of energy as sound is given by the relation

$$[d\mathrm{W}/dt] = \rho_0\kappa^2 a\mathrm{A}^2/(4\pi) = \pi n^2 \rho_0 \mathrm{A}^2/a \qquad (15)$$

We have here assumed that the propagation takes place in a *homogeneous* medium so that the *intensity* of the sound as measured by $|\delta p|^2$ falls off inversely as the square of the distance, and the wave-surfaces are spheres expanding outwards with the velocity of sound. In practice this condition is very far from being realized; the atmosphere, even on an apparently calm day, is the seat of innumerable discontinuities of density due to the presence of eddies and convection currents arising from unequal heating. The amplitude of sound from a fog-signal falls off with distance in a manner which varies very greatly from day to day, the manner of propagation depending on the state of wind and weather to a remarkable degree, as an inspection of the charts of the acoustic survey described in Appendix II. clearly indicates. Under these conditions one must imagine the wave-surface to be undergoing severe distortions as it is being propagated outwards, with the formation at times of so-called "silent zones" and zones of abnormal intensity. Several illustrations of these are to be seen in the charts just referred to.

§ 4. On the Efficiency of Sound-producing Instruments.

The changes of pressure and density which occur in a sound-wave near the limits of audibility are of extremely small magnitude. The question appears to have

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* Rayleigh, 'Phil. Mag.,' vol. 6, pp. 289–305, 1903; 'Scientific Papers,' vol. v., p. 126.

first been investigated by TÖPLER and by BOLTZMANN,[*] who determined a value $|s| = 6{\cdot}5 \times 10^{-8}$ for the maximum condensation in a musical note of pitch $n = 181$, and of sufficient intensity to be just audible. The matter was discussed considerably later by RAYLEIGH,[†] WIEN,[‡] and more recently by WEBSTER,[§] who made use of an absolute "phonometer" of the type described in Part II. of the present paper. These experimenters agree in obtaining for the maximum condensation values of the same order as that given above. Inserting this value in the formulæ of § 2, we obtain for the numerical characteristics of just audible sound-waves of pitch 181, $|s| = 6{\cdot}5 \times 10^{-8}$, $|\partial p|/p_0 = 9{\cdot}2 \times 10^{-8}$, $|\xi| = 1{\cdot}9 \times 10^{-6}$ cm., $|\dot{\xi}| = 2{\cdot}2 \times 10^{-3}$ cm./sec., while $[d\mathrm{W}/dt] = 1{\cdot}0 \times 10^{-4}$ ergs per sec./cm^2.

It will be seen in Part II., from the results of an efficiency test on a powerful fog-signal apparatus, that the above quantities may be many thousand times greater when calculated for the sound-waves generated at the vertex of the conical siren trumpet.

The efficiency of sources of sound with reference to fog-signals seems to have first been discussed by RAYLEIGH [||] in connection with the Trinity House experiments conducted at St. Catherine's Point, Isle of Wight, in 1901.[¶] Actual measurements of the acoustic output of musical instruments were carried out as early as 1902 by WEBSTER,[**] making use of his absolute phonometer. Various experiments agreed in assigning efficiencies of the order of two or three parts in a thousand to several varieties of wind instruments operated by pressures of a few inches of water, while an electrically-driven sound generator was constructed having an efficiency of as much as five parts in a thousand.

It is interesting to make use of the preceding data in connection with the sound-waves generated by fog-sirens operating under normal atmospheric conditions. The "diaphone" described in Part II. gave a signal of six seconds duration each minute: pitch, $n = 174$; air consumption, 14·8 cubic feet per second at a pressure of 23 lbs./sq. in., representing a total available rate of expenditure of energy (calculated adiabatically) during the blast of 35 H.P. In exceptionally calm weather the signal was just audible at a distance of 10 nautical miles (18·4 km.). At this distance the flux of energy across a square centimetre of wave-front (regarded as a plane wave) is given by

$$[d\mathrm{W}/dt] = \tfrac{1}{2}a^3 |s|^2 \rho_0. \qquad (16)$$

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[*] TÖPLER and BOLTZMANN, 'Ann. Phys. Chem.,' 141, pp. 321-352 (1870).

[†] RAYLEIGH, 'Roy. Soc. Proc.,' 26, pp. 248–249 (1877); 'Scientific Papers,' vol. i., p. 328; 'Theory of Sound,' vol. II., p. 432 (1896).

[‡] WIEN, 'Ann. Phys. u. Chem.,' 36, pp. 834–857 (1889).

[§] WEBSTER, 'BOLTZMANN Memorial Volume,' pp. 866–875 (J. A. BARTH, Leipzig, 1904).

[||] RAYLEIGH, 'Phil. Mag.,' 6, pp. 289–305, 1903; 'Scientific Papers,' vol. v., p. 126.

[¶] 'Report of Trinity House Fog-Signal Committee on Experiments Conducted at St. Catherine's Point, Isle of Wight' (Darling and Son, London, 1901).

[**] WEBSTER, *loc. cit.*, p. 872.

Inserting for $|s|$ BOLTZMANN'S estimate, $6\cdot5 \times 10^{-8}$, we obtain for the total flux of energy across a hemisphere of radius $r = 18\cdot4$ km.,

$$\begin{aligned} 2\pi r^2 [dW/dt] &= \tfrac{1}{2} \times (3\cdot32 \times 10^4)^3 \times (6\cdot5 \times 10^{-8})^2 \times 0\cdot0129 \times 2\pi (1\cdot84 \times 10^6)^2 \\ &= 222 \times 10^7 \text{ ergs/sec.} = 0\cdot3 \text{ H.P.} \end{aligned}$$

It will be noticed that the energy propagated as sound at this distance is a very small fraction of the power required to produce it; also that this estimate makes no assumption as to the mode of propagation. We are not justified, however, in taking this estimate of energy flux to hold for all distances as would be required by the inverse square law of propagation, and in particular for the proportion of power converted into sound at the generator itself: actual tests with the Webster phonometer over long distances show that the inverse square law is not even approximately true in consequence of atmospheric refractions, while measurements of acoustic output by a special thermodynamical method indicate that relatively large amounts of power (about 2·4 H.P.) may be converted into sound at the vertex of the siren trumpet. The attenuation of energy-flux to quantities of the order of 0·3 H.P. at 18·4 km. is attributed by the writer to "atmospheric" losses, the greater part of which probably occur in the trumpet itself and in its immediate vicinity. The cause of these losses yet remains to be investigated, and will probably be found to be intimately associated with the question of the abnormal mode of propagation of waves of great intensity, a subject which we shall discuss briefly in the following sections.

§ 5. SOUND-WAVES OF FINITE AMPLITUDE.

(i.) *Note on the Results of Previous Investigations.*

The equation for the propagation of sound-waves of small amplitude may be written in the familiar form

$$\partial^2 y/\partial t^2 = a^2\, \partial^2 y/\partial x^2, \quad \ldots \ldots \ldots \quad (17)$$

where y represents the displacement of a layer of air from the equilibrium position. The derivation of this equation assumes that it is legitimate to neglect higher powers of the condensation s than the first. The exact equations governing the mode of propagation of waves of finite amplitude were first derived by POISSON* as long ago as 1808, and were discussed in further detail by STOKES† in 1848. In the case of adiabatic propagation, the exact equation was first derived by EARNSHAW‡ (1860) in the form

$$(\partial y/\partial x)^{\gamma+1} (\partial^2 y/\partial t^2) = a^2\, \partial^2 y/\partial x^2. \quad \ldots \ldots \ldots \quad (18)$$

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* POISSON, "Mémoire sur la Théorie du Son," 'Journ. de l'Ecole Polytechnique,' vol. VII., p. 319, *et seq.*, 1808.

† STOKES, "On a Difficulty in the Theory of Sound," 'Phil. Mag.,' Nov., 1848 'Mathematical and Physical Papers,' vol. II., p. 51.

‡ EARNSHAW, 'Roy. Soc. Proc.,' Jan. 6, 1859; 'Phil. Trans. Roy. Soc.,' 1860, p. 133.

The discussion of the mode of propagation of waves according to the above equation has been dealt with by Riemann* (1860), Rankine† (1870), Hugoniot‡ (1887, 1889). In an important memoir, Rayleigh§ (1910) gives a critical and historical account of the subject under discussion, and discusses in further detail special solutions of the problem of finite waves and the influence of viscosity and thermal conductivity on their mode of propagation. It is there shown that in the case of adiabatic propagation the velocity u in the medium due to the wave-motion expressed by equation (18) is rigorously given by

$$u = f[x-(a+\epsilon u)\,t], \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where $\epsilon = \frac{1}{2}(\gamma+1)$ and $f[\ldots]$ is an arbitrary function depending on the circumstances of the motion at the instant $t = 0$.

The above solution reduces to the case of isothermal propagation ($\gamma = 1$) previously considered by Poisson,

$$u = f[x-(a+u)\,t]. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

The discussion of the propagation of a wave according to equation (19) in the particular harmonic form

$$u = \mathrm{U}\sin 2\pi\,[x/\lambda-(1+\epsilon u/a)\,nt] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

has been discussed by Stokes‖; it was pointed out that a wave thus represented undergoes a gradual change of form, the condensation overtaking the rarefaction until the motion becomes physically impossible for the least value of t for which $\partial x/\partial u = 0$. At this stage other phenomena due to physical causes not included in the above statement of the problem come into play.¶ Applying this condition to (21) we obtain for the interval t the relation

$$2\pi\epsilon\,|nt| = a\,(1/\mathrm{U})\,(1-u^2/\mathrm{U}^2)^{-\frac{1}{2}} = (1/\mathrm{U})\sec 2\pi\,[x/\lambda-(1+\epsilon u/a)\,nt],$$

from which it follows that discontinuity must occur after an interval not less than that given by

$$t_1 = a/(2\pi\mathrm{U}\epsilon n). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The distance x_1 travelled in this interval lies between two limits assigned by the inequality

$$a^2/(2\pi\mathrm{U}\epsilon n) < x_1 < a^2\,(1+\epsilon\mathrm{U}/a)/(2\pi\mathrm{U}\epsilon n), \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

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* Riemann, 'Gött. Abh.,' t. VIII., p. 43 (1858-9); 'Werke,' 2nd Ed., Leipzig, 1892, p. 157.

† Rankine, 'Phil. Trans.,' vol. 160, p. 277, 1870; 'Misc. Sc. Papers,' p. 530.

‡ Hugoniot, 'Journ. de l'Ecole Polytechnique,' 1887, 1889.

§ Rayleigh, "Aerial Plane Waves of Finite Amplitude," 'Roy. Soc. Proc.,' A, vol. 84, pp. 247–284, 1910; 'Scientific Papers,' vol. v., pp. 573–619.

‖ Stokes, *loc. cit.*

¶ For a discussion of the problem under these conditions see a paper by Taylor, G. I., "The Conditions Necessary for Discontinuous Motion in Gases," 'Roy. Soc. Proc.,' 84, A, 1910, pp. 371–377.

or, in terms of the maximum condensation, $|s| = \mathrm{U}/a$

$$a/(2\pi\epsilon n|s|) < x_1 < a(1+\epsilon|s|)/(2\pi\epsilon n|s|). \quad . \quad . \quad . \quad . \quad . \quad . \qquad (24)$$

By writing $\gamma = 1$ in the above equations we obtain the values for the corresponding case of isothermal propagation given by RAYLEIGH.*

(ii.) *On a Contribution to the Theory of the Propagation of Aerial Plane Waves of Finite Amplitude.*

With a view to the future discussion of the theory of ideal sound-generators, we proceed to examine in greater detail the question of the propagation of aerial plane-waves of large amplitude. Following the main lines of RAYLEIGH's exposition,† we denote by y and $y+\partial y/\partial x\,.\,dx$ the actual positions at time t of neighbouring layers of air whose initial positions are defined by x and $x+dx$. The equation of continuity of mass gives us the relation $\rho_0 = \rho\,\partial y/\partial x$. If the expansions and condensations are supposed to take place according to the adiabatic law, $p/p_0 = (\rho/\rho_0)^\gamma$, we have $p/p_0 = (\partial y/\partial x)^{-\gamma}$. The mass of unit area of the slice is $\rho_0\,dx$, and the force acting on it is $-(\partial p/\partial x)\,dx$, so that the equation of motion, $\rho_0(\partial^2 y/\partial t^2) + (\partial p/\partial x) = 0$, gives on eliminating p and writing $a^2 = (p_0\gamma/\rho_0)$,

$$(\partial y/\partial x)^{\gamma+1}(\partial^2 y/\partial t^2) = a^2\,\partial^2 y/\partial x^2,$$

which is EARNSHAW's equation already quoted. EARNSHAW's solution of the exact equation proceeds on the assumption that there is at every point a definite relation between the particle velocity ($u = \partial y/\partial t$) and the density, $\rho/\rho_0 = (\partial y/\partial x)^{-1}$ in the sound-wave, symbolized by the relation

$$u = \partial y/\partial t = \mathrm{F}(\partial y/\partial x).$$

If we differentiate this equation with respect to t we obtain

$$\partial^2 y/\partial t^2 = [\mathrm{F}'(\partial y/\partial x)]^2(\partial^2 y/\partial x^2).$$

This equation may be identified with EARNSHAW's equation by choosing the arbitrary function F to satisfy the equation

$$[\mathrm{F}'(\partial y/\partial x)]^2 = a^2(\partial y/\partial x)^{-(\gamma+1)},$$

or, writing for brevity $\alpha = (\partial y/\partial x) = \rho_0/\rho$, F is determined from

$$\mathrm{F}'(\alpha) = \pm a\alpha^{-\frac{1}{2}(\gamma+1)}.$$

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* RAYLEIGH, 'Scientific Papers,' vol. v., p. 575.

† RAYLEIGH, 'Sound,' 2nd edition, 1896, vol. II., pp. 31, *et seq.*

Taking the lower sign, corresponding to a wave propagated along the positive direction of the x-axis, we have

$$u = \mathrm{F}(\alpha) = \mathrm{C} + [2a/(\gamma-1)]\,\alpha^{-\frac{1}{2}(\gamma-1)}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

C being a constant of integration which takes into account a possible progressive motion of the medium as a whole. If the velocity of the medium as a whole is U when undisturbed by sound-waves, we have $u = \mathrm{U}$ when $\alpha = 1$, which gives $\mathrm{C} = \mathrm{U} - 2a/(\gamma-1)$, so that the relation between the particle velocity and the density in the medium is given by

$$u = \mathrm{U} - \frac{2a}{\gamma-1}\left[1 - \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{2}(\gamma-1)}\right]. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

It is not difficult to verify that if f is any arbitrary function corresponding to $u = f(t)$ when $x = 0$,

$$u = f\left[t - \alpha^{\frac{1}{2}(\gamma+1)}\frac{x}{a}\right] = \mathrm{U} - \frac{2a}{\gamma-1}\left[1 - \alpha^{-\frac{1}{2}(\gamma-1)}\right] \quad . \quad . \quad . \quad . \quad . \quad (27)$$

is a solution of Earnshaw's equation which may be written in the form

$$\partial u/\partial t = a^2\alpha^{-(\gamma+1)}\,\partial\alpha/\partial x. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

From equation (25) we derive

$$a\,(\partial\alpha/\partial x) = -\alpha^{\frac{1}{2}(\gamma+1)}\,\partial u/\partial x, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

so that (28) becomes

$$\partial u/\partial t = -a\alpha^{-\frac{1}{2}(\gamma+1)}\,\partial u/\partial x. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

Differentiating (27) we have

$$\frac{\partial u}{\partial t} = \left[1 - \tfrac{1}{2}(\gamma+1)\,\alpha^{\frac{1}{2}(\gamma-1)}\left(\frac{x}{a}\right)\left(\frac{\partial\alpha}{\partial t}\right)\right]f'[\ldots]. \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

$$a\frac{\partial u}{\partial x} = \left[-\alpha^{\frac{1}{2}(\gamma+1)} - \tfrac{1}{2}(\gamma+1)\,x\alpha^{\frac{1}{2}(\gamma-1)}\frac{\partial\alpha}{\partial x}\right]f'[\ldots]$$

$$= \left[-\alpha^{\frac{1}{2}(\gamma+1)} + \tfrac{1}{2}(\gamma+1)\frac{x}{a}\,\alpha^{\gamma}\frac{\partial u}{\partial x}\right]f'[\ldots],$$

giving

$$-a\alpha^{-\frac{1}{2}(\gamma+1)}\frac{\partial u}{\partial x} = \left[1 - \tfrac{1}{2}(\gamma+1)\,\alpha^{\frac{1}{2}(\gamma-1)}\frac{x}{a}\frac{\partial u}{\partial x}\right]f'[\ldots]. \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Since $\partial\alpha/\partial t = \partial^2 y/\partial x\,\partial t = \partial u/\partial x$, we notice that (31) and (32) are identical, from which it follows that (30) is satisfied, *i.e.*, that (27) is a complete solution of Earnshaw's equation. From equation (26) we may write the solution in the form

$$u = f\left[t - \frac{x/a}{\{1 + \frac{1}{2}(\gamma-1)(u-\mathrm{U})/a\}^{\frac{\gamma+1}{\gamma-1}}}\right]. \quad . \quad . \quad . \quad . \quad . \quad (33)$$

From equations (33) or (27) we are enabled to trace out the progress of a finite wave corresponding to given velocity conditions at the origin $x = 0$. As has already been mentioned, the wave will give rise to a "discontinuity" after having travelled a distance which, in any given circumstances, may be determined from the complete solution which has just been given. Little is known either theoretically or experimentally regarding the state of affairs which exists in the wave in the neighbourhood of the discontinuity. It is not impossible, as suggested by STOKES, that the discontinuity may give rise to a species of reflected wave which will travel backwards towards the seat of the initial disturbance, thus complicating the state of affairs in the medium as represented by the original equations for finite waves. In applying these equations it is therefore necessary to assume that the waves, supposed to be propagated along a cylindrical tube, are completely absorbed by some mechanism before discontinuity sets in. It is interesting to note that HADAMARD* has pointed out that, under conditions most likely to exist in practice, the discontinuity to which finite plane waves tend might give rise to the formation of vortices. It is easy to see from physical considerations that waves of large amplitude would tend to set up vortices in the neighbourhood of solid obstacles or of pre-existing eddies. Gaseous viscosity and thermal conductivity must play an important part in the sequence of events, but the inclusion of these factors in the equations of propagation complicates the problem beyond hope of solution.

(iii.) *Application of Preceding Theory to the Generation of Finite Waves by the Harmonic Motion of a Piston.*

It will be evident from the remarks already made that the conditions under which waves of large amplitude are generated and propagated have an important bearing on the theory and design of fog-signal sound generators. Owing to the limitations of the existing theory in leaving out of account thermal conduction and viscosity, it is desirable that the subject be studied from an experimental point of view. A simple apparatus capable of practical realization consists of a circular piston made to vibrate harmonically in a cylinder of sufficient length that the effect of the end open to the free atmosphere may be neglected. One of the first questions to be studied is the formation of the discontinuity.

If the motion of the piston at $x = 0$ is given by

$$u = u_0 \sin 2\pi nt;$$

the velocity in the wave at distance x from the origin is given by

$$u = u_0 \sin 2\pi n \left[t - \frac{x/a}{\{1+\frac{1}{2}(\gamma-1)\,u/a\}^{\frac{\gamma+1}{\gamma-1}}} \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

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[*] HADAMARD, J., 'Leçons sur la Propagation des Ondes,' Paris, 1903. The same idea has also been advanced in another connection by FESSENDEN, R. A., 'Science,' Oct. 17, 1913.

The discontinuity occurs for the least value of t for which $\partial x/\partial u = 0$: writing $\xi = [1+\frac{1}{2}(\gamma-1)\,u/a]$, this condition may be written $\partial x/\partial\xi = 0$.

In the application of these formulæ to air, we take $\gamma = 1{\cdot}40$, so that (34) may be written

$$x = at\xi^6 - a\xi^6/(2\pi n)\sin^{-1}[5\,(1-\xi)\,a/u_0]. \qquad (35)$$

The condition $\partial x/\partial\xi = 0$ leads to the equation

$$x+\tfrac{5}{6}a^2\xi^7/(2\pi n u_0)\sec 2\pi n\,(t-\xi^{-6}x/a) = 0, \qquad (36)$$

where ξ is given in terms of x and t by equation (35), from which it is seen that discontinuity will occur for some value of t for which $2\pi n\,(t-\xi^{-6}x/a)$ lies between $\frac{1}{2}\pi$ and π. In this interval it follows from equation (34) that u is positive, so that the minimum value of ξ is unity. Thus we may assert from (36) that the discontinuity will certainly not occur in the distance x given by

$$x = \tfrac{5}{6}a^2/(2\pi n u_0), \qquad (37)$$

this estimate agreeing with the lesser estimate of the two given in (23) when the numerical value for $\epsilon = \frac{1}{2}(\gamma+1) = 1{\cdot}20$ is inserted therein.

It is not without interest to calculate the rate at which the vibrating piston communicates energy to the atmosphere in the form of sound-waves. The rate at which the piston (of area S) does work is given by

$$\dot{\mathrm{W}} = \mathrm{S}pu = p_0\mathrm{S}\,(\rho/\rho_0)^\gamma\,u,$$

where u is the velocity of the piston and ρ is the density of the air over the section in contact with the piston.

From the theory of finite waves the density is given in terms of the velocity in the wave by equation (26) in which we write $\mathrm{U} = 0$,

$$\rho/\rho_0 = [1+\tfrac{1}{2}(\gamma-1)\,u/a]^{2/(\gamma-1)}, \qquad (38)$$

so that

$$\dot{\mathrm{W}} = p_0\mathrm{S}\,[1+\tfrac{1}{2}(\gamma-1)\,u/a]^{\frac{2\gamma}{\gamma-1}}\,u,$$

and the average rate at which work is done is given by the expression

$$[\dot{\mathrm{W}}] = p_0\mathrm{S}\,\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} u\,\{1+\tfrac{1}{2}(\gamma-1)\,u/a\}^{\frac{2\gamma}{\gamma-1}}\,dt. \qquad (39)$$

Taking $\gamma = 1{\cdot}40$, the above expression may be evaluated in finite terms for a harmonic motion of the piston, $u = u_0\sin(2\pi nt)$.

Expanding $\{1+\frac{1}{2}(\gamma-1)\,u/a\}^{\frac{2\gamma}{\gamma-1}} = (1+\frac{1}{5}u/a)^7$, and integrating term by term, we obtain the expression

$$[\dot{\mathrm{W}}] = \tfrac{7}{10}\mathrm{S}\,(p_0u_0^{\,2}/a)\left[1+\tfrac{15}{4}\left(\frac{u_0}{5a}\right)^2+\tfrac{15}{8}\left(\frac{u_0}{5a}\right)^4+\tfrac{5}{64}\left(\frac{u_0}{5a}\right)^6\right] \qquad (40)$$

Even when u_0 approaches half the velocity of sound, this expression differs by only some four per cent. from the corresponding expression for waves of small amplitude as given by equations (7) and (10), to which (40) reduces when u_0/a is negligible.

§ 6. On the Thermodynamic Basis for the Measurement of the Acoustic Output of a Compressed Air Siren.

It is manifest from what has been said in the preceding sections that the theory of finite waves gives us no basis according to which the acoustic output of a siren may be calculated. We may, however, develop experimental means of estimating the rate at which energy is converted into sound. If we denote by $\dot{M}$ the total rate of air consumption, we suppose that a certain part $\dot{m}$ is utilized in the production of external work propagated away as sound, and that the work so done is performed adiabatically from pressure, density and absolute temperature p_1, ρ_1 and Θ_1, respectively, to atmospheric conditions represented by p_0, ρ_0 and Θ_0. The calculation of acoustic output will depend on the particular mechanism by which the utilizable air is allowed to perform external work. That representing conditions in a siren may be represented as follows:—We suppose the ports to be suddenly opened, allowing a volume v_1 of air under conditions (p_1, ρ_1, Θ_1) to pass into the resonator. We then suppose the ports to close while the volume of air v_1 expands adiabatically to a volume v_0 under atmospheric conditions (p_0, ρ_0, Θ_0), performing external work in compressing the layers of air in the resonator ahead of it, thus generating a single sound-wave. This cycle of operations is supposed to be repeated n times a second, so that in terms of the effective mass-flow

$$\dot{m} = n\rho_1 v_1 = n\rho_0 v_0. \qquad (41)$$

The remainder of the air-consumption $(\dot{M}-\dot{m})$ may be taken to include continuous leakage of air between the siren-cylinders, and that part of the intermittent flow through the ports which is in a violent state of eddy-motion. This eddy-motion probably dies out an appreciable fraction of a period after the ports are closed, so that the full expansion resulting from this portion of the flow is developed out of phase with the main wave and contributes nothing on the average to the energy in the wave. This portion will be referred to as "leakage." The work done per cycle by the volume v_1 of air is

$$\int_{v_1}^{v_0} p\,dv = \frac{p_1 v_1}{\gamma-1}\left[1-\left(\frac{v_1}{v_0}\right)^{\gamma-1}\right].$$

Since the work is performed adiabatically, the temperature of this volume of air after expansion is given by $(v_1/v_0)^{\gamma-1} = \Theta_0/\Theta_1$, so that the rate at which work is done in the n cycles per second may be written in either of the forms

$$\dot{w} = \frac{np_1 v_1}{\gamma-1}\left[1-\left(\frac{p_0}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right] = \frac{p_1}{\rho_1}\frac{\dot{m}}{\gamma-1}(\Theta_1-\Theta_0), \qquad (42)$$

making use of (41) and the adiabatic relation $p_1 v_1{}^{\gamma} = p_0 v_0{}^{\gamma}$.

If R be the gas-constant, we have $p_1/\rho_1 = \mathrm{R}\Theta_1$. In terms of the specific heat of air at constant pressure and volume, C_p and C_v, we have $\mathrm{R} = \mathrm{J}(\mathrm{C}_p - \mathrm{C}_v)$, where J is the mechanical equivalent of heat. Since $\gamma = \mathrm{C}_p/\mathrm{C}_v$ we have $\mathrm{R} = \mathrm{JC}_v(\gamma-1)$, so that (42) may be written

$$\dot{w} = \mathrm{JC}_v\dot{m}\Theta_1\left[1-(p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right] = \mathrm{JC}_v\dot{m}(\Theta_1-\Theta_0). \quad . \quad . \quad . \quad . \quad . \quad (43)$$

The portion of the air-consumption $(\dot{\mathrm{M}}-\dot{m})$ due to leakage performs no external work (except the negligibly small amount done against intramolecular attraction represented by the Joule-Thomson effect), and thus passes through the siren without change of temperature, but mixes with the effective air to give a temperature Θ at some distance from the siren ports, sufficiently far downstream for eddies to have died down and the flow to have become regular except for the motion of the medium due to sound-waves. In these circumstances, as there is no rate of loss of heat, Θ is given by

$$\mathrm{C}_v\dot{\mathrm{M}}\Theta = \mathrm{C}_v\dot{m}\Theta_0 + \mathrm{C}_v(\dot{\mathrm{M}}-\dot{m})\Theta_1,$$

or

$$\dot{\mathrm{M}}(\Theta_1-\Theta) = \dot{m}(\Theta_1-\Theta_0).$$

We thus have for the rate at which external work is propagated away as sound from the siren the expression

$$\dot{w} = \mathrm{JC}_v\dot{\mathrm{M}}(\Theta_1-\Theta), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

in which $\dot{\mathrm{M}}$ and $(\Theta_1-\Theta)$ are experimentally measurable quantities. As a standard of comparison we shall adopt an ideal siren having no "leakage" and operating according to the cycle described. Replacing $\dot{m}$ by $\dot{\mathrm{M}}$ in the first of equations (43), the acoustic output of such a siren may be written

$$\dot{\mathrm{W}} = \mathrm{JC}_v\dot{\mathrm{M}}\Theta_1\left[1-(p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right]. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

In terms of this standard we may write for the "acoustic efficiency" of the siren the expression

$$\eta = \frac{\dot{w}}{\dot{\mathrm{W}}} = \frac{(\Theta_1-\Theta)}{\Theta_1\left[1-(p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right]}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

The results of tests on an actual siren (a "diaphone") based on the above theory are described in Appendix III., together with the precautions to be observed in carrying out the necessary temperature measurements.

The theory of the present section enables us to estimate the acoustic output of types of fog-signal apparatus in which the compressed air is utilized to produce sound in other ways than by escape through siren ports intermittently opened and closed. For instance, by a suitable arrangement of valves as in a compressed-air rivetter, or in the "driving head" of the piston of the diaphone, it might be feasible to cause a piston to vibrate through a large amplitude in a cylinder opening out into a conical resonator, thus realizing the type of apparatus considered theoretically in Section 5 (ii). Whether such a form of apparatus would be more efficient than the best of existing types of sirens is a question which only a quantitative test can decide.*

§ 7. On the Theoretical Calculation of the Characteristics of Finite Waves emitted by a Compressed Air Siren.

In the following section an attempt is made to establish the theory of a compressed air siren, combining the results derived for the adiabatic flow of air through an orifice with the formulæ obtained in the preceding sections for the characteristics of aerial plane waves of finite amplitude. While such a theory must, in our present state of knowledge, be very imperfect owing to the neglect of many complex conditions met with in reality, the results thus obtained for what may be called an "ideal siren" may serve a useful purpose in giving in a general way an idea of the state of affairs which may be met with in practice.

The essential features of a siren consist of a reservoir in which air is maintained at constant pressure p_1 and ρ_1, an orifice or series of orifices periodically opened and closed allowing the air to escape in intermittent puffs into the resonator, which we take for simplicity to be a long cylindrical tube of cross-section S. The pressure and density in the sound-waves a short distance from the ports of the siren we denote by (p, ρ); these are the pressures and densities in the finite wave generated in the cylindrical resonator, and are therefore connected with the velocity u in the wave by equation (26). We denote by (p_0, ρ_0) atmospheric pressure and density.

Applying **Bernouilli**'s equation to the steady adiabatic flow of a gas through an orifice, we obtain for the velocity q at the low-pressure side of the orifice where the pressure is p

$$q^2 = 2\int_p^{p_1} \frac{dp}{\rho}. \qquad (47)$$

This result assumes that the flow is stream-line, and that at a sufficient distance from the orifice on the upstream side where the pressure is p_1 the velocity is negligible. Integrating (47) for adiabatic flow when $p/p_1 = (\rho/\rho_1)^\gamma$ we obtain for the mass-flow the expression

$$\tfrac{1}{2}q^2\rho^2 = p_1\rho_1 \frac{\gamma}{\gamma-1}\left[\left(\frac{\rho}{\rho_1}\right)^2 - \left(\frac{\rho}{\rho_1}\right)^{\gamma+1}\right], \qquad (48)$$

which is a well-known formula due to **Saint-Venant** and **Wantzel**.†

If we denote by A (t) the total *effective area* of the ports and assume that formula

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* [*Added February* 14, 1919.—In the opinion of some practical fog-signal engineers the actual velocity of the air in the trumpet of a diaphone has an important effect in determining the loudness of the signal and its atmospheric penetration.]

† **Lamb**, 'Hydrodynamics,' 3rd edition, 1906, p. 23. The limitation of this formula forms the subject of a recent discussion by **Rayleigh**, 'Phil. Mag.,' vol. 32, Aug., 1916, pp. 177–187.

(48) holds at every instant of time during which A (t) varies, the rate of mass-flow through the ports of the siren is given by

$$\dot{m} = q\rho \mathrm{A}(t). \quad \ldots \ldots \ldots \quad (49)$$

If, now, we assume that the *entire* flow contributes to the velocity u in the sound-wave in the cylindrical resonator of area S in the neighbourhood of the siren ports $(x = 0)$, the equation of continuity gives

$$\dot{m} = \rho u \mathrm{S}, \quad \ldots \ldots \ldots \quad (50)$$

so that from (48) (49) and (50) we obtain for the velocity in the wave the expression

$$u = \frac{\mathrm{A}(t)}{\mathrm{S}}\left[\frac{2\gamma}{(\gamma-1)}\frac{p_1}{\rho_1}\left(1-\frac{\xi^2}{\kappa}\right)\right]^{\frac{1}{2}}, \quad \ldots \ldots \ldots \quad (51)$$

where we have written $\kappa = (\rho_1/\rho_0)^{\gamma-1}$ and $\xi = (\rho/\rho_0)^{\frac{1}{2}(\gamma-1)}$. Under the assumption just mentioned, writing $\mathrm{U} = 0$ in (26),

$$u = -\{2a/(\gamma-1)\}(1-\xi) = -\{2/(\gamma-1)\}(\gamma p_0/\rho_0)^{\frac{1}{2}}(1-\xi). \quad \ldots \quad (52)$$

Identifying (51) and (52) we are enabled to solve for ξ from the quadratic

$$\xi^2[1+\phi(t)]-2\xi+[1-\kappa\phi(t)] = 0 \quad \ldots \ldots \ldots \quad (53)$$

where we have written

$$\phi(t) = \tfrac{1}{2}(\gamma-1)[\mathrm{A}(t)/\mathrm{S}]^2.$$

The root of (53) which makes $\xi = 1$ for $\kappa = 1$ is

$$\xi = (\rho/\rho_0)^{\frac{1}{2}(\gamma-1)} = \frac{1+[1-\{1+\phi(t)\}\{1-\kappa\phi(t)\}]^{\frac{1}{2}}}{1+\phi(t)}. \quad \ldots \ldots \quad (54)$$

Inserting this value of ξ in equation (52) we obtain the initial velocity conditions, so that from the results of § 5 (ii.), we are enabled (theoretically) to trace the progress of the wave generated by any arrangement of siren ports for which the function A (t) may be expressed as a function of the time.

It will be evident that in the problem under consideration any attempt to estimate the rate at which energy is transmitted along the resonator can have little meaning, as such an expression will include the energy of translation of the air in the resonator as a whole, in addition to what may be called the "acoustic output." The energy transmitted as sound at a distance will depend on the type of wave-motion which results after discontinuity has set in. The present theory, which takes no account of energy dissipation, is entirely inadequate to inform us on this subject and requires to be supplemented by data from suitable experiments which will be referred to in Part II.

PART II.—ON THE MEASUREMENT OF SOUND INTENSITY AND OF THE ACOUSTIC OUTPUT OF FOG-SIGNAL APPARATUS.

§ 8.—NOTE ON PREVIOUS FOG-SIGNAL EXPERIMENTS.

As the determination of the physical principles underlying the design of sound-generating machinery is of great importance with reference to the construction of these aids to navigation, the testing of fog-signal equipment has in the past been made the subject of several lengthy and detailed reports. The mode of propagation of sound-waves under the conditions which exist at sea has also at various times engaged the attention of a number of scientific men. Among the more important investigations we may mention TYNDALL'S experiments,* carried out at the South Foreland in 1874 and HENRY'S Report† published in the same year. In these experiments the decrease of intensity with distance and the effect of winds, fog and other atmospheric conditions on the audibility of the signals were investigated. Intensity was estimated in terms of audibility as judged by the unaided ear. The results are now well known and are described in considerable detail in text-books and treatises on sound.‡

An extensive series of tests, carried out at a large number of stations on the North Atlantic coast of the United States, are described in detail in LIVERMORE'S Report§ published in 1894. Here an attempt was made to estimate the intensity of sound in terms of a physical scale. While the ear still remained the instrument of comparison, observations were controlled by means of standards consisting of small musical instruments whose notes imitated in pitch and quality that of the fog-signal as heard from a considerable distance. These were enclosed in small sound-proof boxes, and the intensity of the sound was varied by a sliding cover which could be adjusted to open to different sized apertures. It is stated that estimates of intensity obtained in terms of this arbitrary scale by different observers proved to be in satisfactory agreement.

In 1901 a detailed report was issued by a Committee of the Trinity House|| on experiments carried out at St. Catherine's Point, Isle of Wight, under the scientific direction of Lord RAYLEIGH and Sir THOMAS MATTHEWS. These tests were for the most part confined to an investigation of the relative merits of various forms of sound

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* TYNDALL, "On the Atmosphere as a Vehicle of Sound," 'Phil. Trans.,' vol. 164, pp. 183–244. An account of these experiments is given in TYNDALL'S 'Sound.'

† HENRY, 'Report of the Lighthouse Board of the United States for the year 1874,' Washington.

‡ RAYLEIGH, 'Sound,' 1896, vol. II., p. 129, *et seq.*; LAMB, 'Dynamical Theory of Sound,' 1910, pp. 216–222.

§ LIVERMORE, W. R., "Report upon Fog-Signal Experiments," 'Report of the U.S. Lighthouse Board,' Appendix No. V., 1894, Washington.

|| 'Report of the Trinity House Fog-Signal Committee on Experiments conducted at St. Catherine's Point, Isle of Wight,' 1901. (Published by Darling & Son, London, 1901.)

generators, the estimates of relative intensity being made by ear and indicated by numbers between 1 and 10. For long-range work the superiority of the motor-driven siren operating at about 25 pounds air-pressure was definitely established; in weather conditions associated with a smooth sea, a pitch of 182 complete vibrations per second was found to be most suitable, while a high pitch note of 295 vibrations per second was heard to better advantage during high wind and a rough, noisy sea.

The scientific aspect of the preceding tests is discussed at some length by Lord RAYLEIGH in a later paper,* it is there pointed out that the increase of power required to operate the sirens so as to generate more powerful sound-waves is entirely out of proportion to the gain in range of audibility. This point is well illustrated by the fact that when the high note of the Scotch siren was sounded, energy was consumed at the rate of about 600 horse-power. The experiments just referred to constitute a final practical test of particular forms of sirens, in that the signals are judged under the same conditions and by the same means as when they are issued as signals to navigators. While there is no difficulty in thus estimating the relative merits of various forms of sound-generating apparatus it is evident that very little information is to be derived in this way as to the proportion of power actually converted into sound or as to the causes of the very large waste of energy which is known to occur in all sound-producing instruments.

An account of recent researches carried out in France is given very briefly by RIBIÈRE,† who mentions several unsuccessful attempts to construct instruments for the purpose of measuring sound-intensity. In the French Lighthouse Service a study of the influence of atmospheric conditions has been made statistically by keeping daily records at various fog-signal stations of the audibility of daily test-signals sent out from neighbouring stations. RIBIÈRE also points out that the sound-waves emitted by a powerful siren are probably different in character from waves of ordinary intensity, and that in the former case the differential equations for waves of small amplitude no longer apply. The question of the acoustic efficiency of fog-sirens is mentioned as one of the unsolved problems of the subject and the importance of its solution is emphasized.

In order to obtain experimental data to form a basis for a discussion of the various problems mentioned above, it was thought desirable by the writer to undertake a systematic investigation of the subject with the experimental means now available for attacking the difficulties mentioned. Owing to the elegant construction of the form of siren adopted in recent years by the Canadian Government (the "diaphone") and the ease with which the air pressure and air consumption could be controlled and varied, successful efficiency tests were carried out by the thermodynamical method

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* RAYLEIGH, "On the Production and Distribution of Sound," 'Phil. Mag.,' vol. 6, pp. 289–305, 1903. 'Scientific Papers,' vol. v., No. 126.

† RIBIÈRE, C., 'Phares et Signaux Maritimes,' Octave Doin et Fils, Paris, 1908. In this work references are given to important technical papers on the subject of fog-signals up to the year 1908.

devised by the writer. The excellent pitch regulation and relatively pure quality of note emitted by the diaphone made the use of the Webster phonometer in the measurement of sound intensity at a distance especially reliable.

§ 9. DESCRIPTION OF THE DIAPHONE.

The essential features of this modification of the siren are shown in fig. 1, where the principal dimensions of the diaphone actually tested at Father Point are also indicated. The apparatus consists essentially of a brass cylinder into which fits accurately a hollow piston. The head of this piston is of somewhat larger size and fits into a corresponding cylinder fitted with valve-ports so arranged that the admission of compressed air into this driving cylinder (referred to as "driving air") causes the piston to oscillate through a small amplitude (0·15 inch) at half the frequency of the note which it is desired to produce. Both the cylinder and piston are cast of brass and carry on the outer surface of the former and the inner surface of the latter, six light longitudinal ribs; in this way the cylinder and piston may be cut transversely by a series of narrow ports ($\frac{1}{16}$ inch wide) at equal distances apart. As the piston vibrates the main air supply (referred to as the "sounding air") is admitted intermittently from a cast-iron chamber completely surrounding the cylinder and connected through a large relay valve to the compressed-air tanks and compressors.

The variation of pitch with pressure (referred to as "pitch regulation") was measured by means of the phonometer and was found to be relatively small; it is seen from Table III. of Appendix I. that the pitch only increases from 169 to 182 complete vibrations per second for an increase of operating pressure from 12 to 27 lbs./sq. in. above atmospheric. This characteristic, which contributes greatly to the satisfactory performance of the instrument, is probably due to the fact that the frequency is governed largely by the mass of the piston and the elastic reaction of the air in the trumpet (toned to resonance at pitch 180) and in the space behind the piston-head ("cushioning effect").

The operation of the valves so as to give the blasts at the required intervals is automatic. By means of a suitably adjusted cam mechanism connected to the main shaft of the engine driving the compressors, a small valve is first of all opened causing a second valve to admit the "driving air" to the driving cylinder, thus setting the piston into vibration; the same valve also admits air into a large relay valve, allowing the main "sounding air" to pass into the diaphone a fraction of a second later, so that the note begins to sound only when the piston has attained its normal frequency. In fact, the sharp commencement of the note and its sudden termination by a rapid fall in pitch during a small fraction of a second is characteristic of the diaphone signal and is very favourably commented on by navigators as entirely distinct from any siren note which might be sounded from a passing ship and of great value in determining the direction of the sound. During the tests carried out

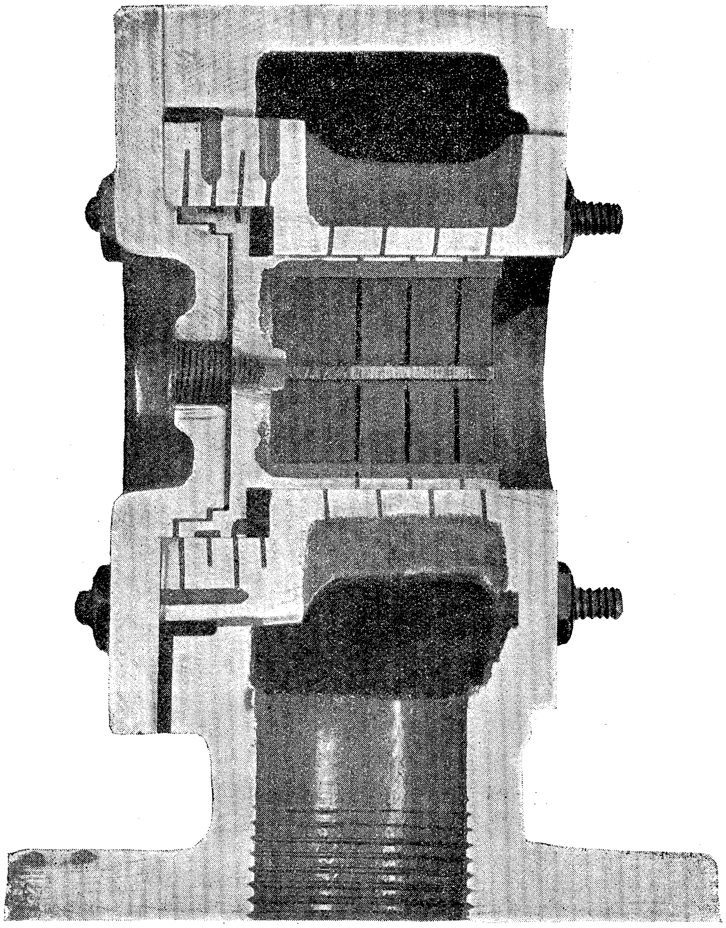

Fig. 1. Small model of the diaphone sectioned to show details of construction.

The principal dimensions of the diaphone tested at Father Point are as follows:—

Piston.—Outer diameter $4\frac{1}{4}$ inches; diameter of driving head 6 inches. Weight $3\frac{1}{4}$ lbs. The piston contained 10 ports $\frac{1}{16}$ inch wide at intervals of $\frac{5}{16}$ inch. Amplitude of piston vibration at 25 lbs. pressure, about 0·15 inch; frequency, 90 complete oscillations per second; ports twice opened during a complete vibration, giving rise to sound-wave of pitch 180.

Trumpet.—Conical semi-vertical angle 6°·5; diameter of large opening $16\frac{1}{2}$ inches; diameter at piston $4\frac{1}{4}$ inches. Slant length to edge of piston 4 feet 10 inches. Over all length 0·66 × wave-length. Resonance frequency of trumpet 180 complete vibrations per second.

Note.—In the Father Point diaphone (1903 model) the exhaust from the driving cylinder discharges into the trumpet. In later designs, as that shown in fig. 1, the exhaust (which is out of phase with the main sounding air) is discharged into the atmosphere outside of the trumpet, thereby improving to some extent the acoustic output. The writer is indebted to Mr. J. P. NORTHEY, of Toronto, for the above information and for the loan of the sectioned model from which the photograph reproduced above was made. For further details of the apparatus see NORTHEY, J. P., United States Patents, No. 736,428, August 18, 1903; No. 879,190, February 18, 1908; No. 973,960, October 25, 1910; No. 1,016,187, January 30, 1912.

by the writer this characteristic termination was sometimes heard when the sustained note was completely inaudible.

The air consumption is regulated by a set screw on the main valve; by adjusting this screw so as to allow the valve more or less clearance, the air consumption is regulated until the amount consumed per blast is equal to the pumping capacity of the compressors between blasts. The pressure then attains a stationary state and the signals are issued automatically at the proper intervals without further attention on the part of the station operator.

In fig. 3 is drawn to scale the diaphone tested by the writer at Father Point, showing schematically the arrangement of the differential thermometers employed in the acoustic output determinations. The short conical trumpet (semi-vertical angle $6^\circ\!\cdot\!5$, over all length $= 0\cdot66 \times$ wave-length) has been found to be the most efficient as a result of numerous tests carried out by the makers and the Canadian Government engineers.* This conclusion agrees with the practice of the French Lighthouse Service.† From the evidence discussed in the present paper as to the propagation of fog-signal sound-waves as waves of finite amplitude, it would appear that the function of the trumpet as a resonator is limited by serious propagation losses occurring before spherical divergence reduces the amplitude to such small values that these losses become negligible. It is hoped to study this aspect of the subject experimentally by the method of the oscillating valve mentioned in the next section; data thus obtained may be useful in deciding the most efficient form of trumpet for different purposes.‡

§ 10. Note on the Practical Measurement of the Characteristics of Sound-Waves.

Although several laboratory methods have been successfully employed in the measurement of sound intensity, none of these seem to have been suitable for service under the exacting conditions arising in carrying out tests on fog-signal generators. It is sufficient to mention two of these methods, both of which enable the compression in a sound-wave to be measured in absolute units, and at the same time do not depend on the theory of propagation of sound-waves of small amplitude. Both of these methods would seem capable of employment under special conditions in the

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* The original diaphone was invented by Dr. Owen Hope-Jones, U.S. Patent, No. 702,557, June 17, 1903. Its utilisation for fog-alarm purposes was first suggested by Lieut.-Col. Anderson, Chief Engineer of the Department of Marine and Fisheries of Canada, who, with his chief assistant, Mr. B. H. Fraser, determined from numerous tests the lines along which the diaphone evolved into full-sized fog-signal apparatus in the hands of Mr. J. P. Northey, of Toronto. The present diaphones are the results of several improvements and modifications due to Mr. Northey which have been made the subject of a number of patents dating from 1903. (See under description of fig. 1.)

† 'Trinity House Report,' p. 32 (see footnote, p. 227, above).

‡ [*Added February* 14, 1919.—For conclusions on this point resulting from more recent work, see footnote, p. 247.]

measurement of the wave-form of the sound-waves emitted by fog-signal generators and in studying the effect of the trumpet on the propagation losses.

TÖPLER and BOLTZMANN'S* method, based on the theory of the interferometer, measures the change of optical path of a beam suitably divided by a half-silvered mirror in such a way that one of the beams travels through air subjected to compression and rarefaction, while the other passes through undisturbed air. The two beams are brought together by a second optical mirror under conditions which give rise to interference fringes. The compressions and rarefactions in the sound-wave give rise to synchronous shiftings of the fringes which may either be photographed on a rapidly moving band of sensitive paper† or examined in detail by a stroboscopic method. The change of density in the air at any point in the wave may be easily calculated in absolute units and hence the corresponding compression.

More suitable for practical purposes is a method first employed by RAPS,‡ which may be referred to as the "oscillating or synchronous valve method." In this case a valve connected to a sensitive manometer is operated by mechanical means so as to open and close synchronously with the period of the source of sound; if the time during which the valve remains open is sufficiently small compared to the period of the sound-wave, the pressure registered will give the compression in the sound-wave at some particular phase. By advancing the phase gradually it becomes possible to trace out the complete wave-form. By this means RAPS was able to measure compressions as high as 0·035 atmosphere. It would seem that this method is well adapted to the study of the powerful sound-waves generated by modern fog-signal machinery.

§ 11. NOTE ON THE WEBSTER PHONOMETER.

As a result of extensive researches carried out by Prof. A. G. WEBSTER, of Clark University, a portable instrument capable of measuring the characteristics of sound-waves over a wide range of pressure amplitudes and under most severe weather conditions is now available for investigating the distribution of sound in the neighbourhood of fog-signal generators. The construction of the particular instrument employed by the writer§ will readily be understood from fig. 2. It consists of a

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* TÖPLER and BOLTZMANN, 'Ann. d. Phys. u. Chem.,' 141, pp. 321–352, 1870. In an account of experimental work carried out in France on the measurement of sound in relation to fog-signals, RIBIÈRE mentions (footnote, p. 228) that interference methods were attempted, but without success, under practical conditions. Preliminary experiments along these lines with the Jamin refractometer led the writer to the same conclusion.

† RAPS, "Ueber Luftschwingungen," 'Ann. d. Phys. u. Chem.,' 50, pp. 193–220, 1893.

‡ RAPS, "Zur objectiven Darstellung der Schallintensität," 'Ann. Phys. u. Chem.,' 36, pp. 273–306, 1888.

§ An early form of this instrument is described by WEBSTER as early as 1904 (see footnote, p. 216). Since the date of construction of the phonometer described above (1913), the instrument has been considerably improved by its inventor.

telescoping cylindrical Helmholtz resonator capable of adjustment to any required pitch by suitably adjusting its volume. Over a circular aperture at the back of this resonator is clamped a mica disc, at the centre of which is firmly fastened a brass pin carefully ground to a fine point. At right angles to this pin, held in a fork carried by the frame of the resonator and capable of fine screw adjustments in two directions at right angles, is mounted a thin steel strip which may be so adjusted that the point of the pin above referred to rests in contact with the strip at any required distance from the neutral axis. A slight displacement of the disc thus causes the strip to rotate through a small angle. This rotation is magnified into an easily measurable deflection by viewing the light from the filament of a small tungsten lamp, reflected from a small concave mirror attached to the steel strip, into a micrometer eye-piece fitted with a suitable graduated transparent scale. When the diaphragm is at rest, the image of the filament is seen sharply defined against the micrometer scale; when a sound-wave of the proper pitch passes over the instrument forced oscillations are set up in the air contained in the resonator. The diaphragm (whose free period is much higher than that of the sound-wave to be measured) is thus set into vibration and the image of the filament is drawn out into a luminous band whose breadth may easily be measured to an accuracy of about 1 per cent.

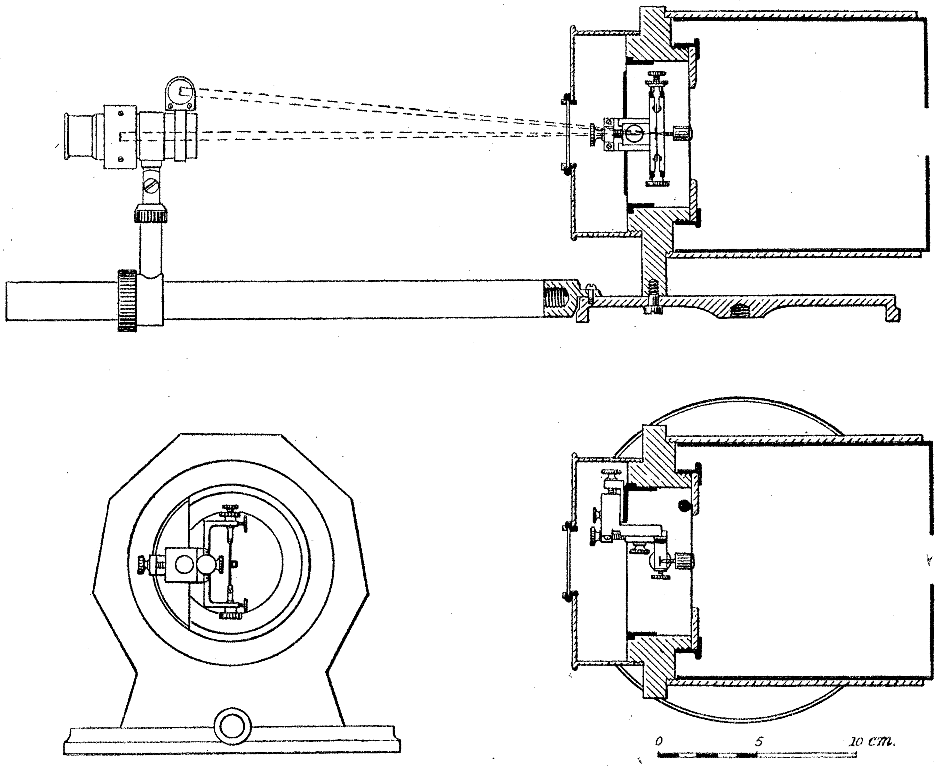

Fig. 2. The Webster phonometer.
Designed by Prof. **Webster** for the Father Point tests.

For any given adjustment of the phonometer the breadth of this band is proportional to the amplitude of vibration of the centre of the diaphragm, therefore to the compression of the air in the resonator, and finally to the compression in the sound-wave in the atmosphere outside.

The conversion of the measured width of this luminous band (referred to as the "phonometer reading") into the pressure amplitude of the sound-wave expressed in absolute units requires the determination of the "constant" of the instrument. This is accomplished in several ways by Prof. WEBSTER. The most convenient method of determining the "constant" is by taking simultaneous measurements of the amplitude of the waves from a constant source of sound by means of the instrument to be calibrated and by a "standard phonometer." In the latter instrument the amplitude of vibration of the diaphragm is measured directly by an interference method combined with a stroboscopic arrangement for observing the fringes. From the mathematical theory of the motion of the diaphragm vibrating under the influence of aerial vibrations in the resonator, it is possible to express the compression in the sound-wave outside the instrument in terms of the phonometer reading, making use of separately determined inertia, elastic and damping constants of the vibrating system.

Through the courtesy of Prof. WEBSTER, a phonometer specially designed for the Father Point tests was constructed under his immediate supervision, and was successfully employed under the severe practical conditions met with. An account of experiments carried out with the Webster phonometer in connection with the measurement of sound from the diaphone is given in Appendix I., where further details relating to its manipulation and characteristics are given.

§ 12. ON THE INFLUENCE OF METEOROLOGICAL CONDITIONS ON THE PROPAGATION OF SOUND.

(i.) *Introduction.*

The capricious behaviour of sound-waves propagated in the open atmosphere has been attributed to the existence of innumerable discontinuities of temperature, density and humidity, and to refraction by gradients of wind-velocity.*

It has long been known that the retarding effect of the earth's surface on the velocity of the wind is to give rise to a velocity gradient. It was first pointed out by STOKES† in 1851, that as a result, a sound-wave travelling against the wind will have its wave-front continually tilted upwards, so that the sound tends to pass over the

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* An excellent summary, with an extensive bibliography of the work of previous observers, is given by BATEMAN, "The Influence of Meteorological Conditions on the Propagation of Sound," 'Monthly Weather Review,' 42, May, 1914, pp. 258–265.

† STOKES, 'Brit. Assoc. Rep.,' 1857, p. 22; or 'Mathematical and Physical Papers,' vol. IV., p. 110. See also RAYLEIGH'S 'Sound,' 1896, vol. II., p. 132.

head of an observer at a distance. On the contrary, when travelling with the wind, the wave-front is continually tilted downwards, thus explaining the familiar fact that sound may be more easily heard, and at a greater distance, when the observer is to leeward of the source. This explanation was given independently by REYNOLDS[*] and confirmed by a number of observations. These conclusions have been supported, on the whole, by the results of the various fog-signal tests already referred to During the last few years, through the development of aviation, a great deal of attention has been directed to the investigation of the structure of the atmosphere. It has been known for a long time that the wind near the earth's surface is the seat of innumerable eddies.[†] Quite recently the subject of eddy motion in the atmosphere has been definitely formulated in mathematical terms by TAYLOR.[‡] Observations by DINES[§] and others on the gustiness of the wind are interpreted by TAYLOR as indicating that the eddy-motion has a tolerably regular structure, and that in a wind of given velocity and vertical gradient, a fairly definite diameter may be assigned to the eddies. In atmospheric movements these eddies, which have a certain degree of permanence, play the part of molecules in the kinetic theory of gases. Thus the conception of "eddy-viscosity" and "eddy-conductivity" as regards the transfer of momentum and heat in the atmosphere is employed with success in the interpretation of many meteorological phenomena.

The conception of eddy-motion has recently been employed by TAYLOR[||] to account for the attenuation of sound in a windy atmosphere. It is shown that eddies scatter a certain portion of the energy of the sound-waves in all directions at the expense of that in the wave-train advancing in any particular direction. The mechanism of attenuation of sound by eddies is thus somewhat analogous to that of the extinction of light in the atmosphere by the scattering effect of dust or fog particles. In the opinion of the writer many of the results observed in connection with fog-signal tests may be interpreted in terms of the eddy-motion theory. For instance, the remarkably loud and well-sustained echoes often observed after a loud blast has been sounded are probably nothing more than the scattered and re-scattered sound-waves reaching the observer from all directions. It thus appears that in the eddy-structure of the atmosphere we must look for the interpretation of TYNDALL'S state of "acoustic flocculence," while the eddies themselves are the realization of his "acoustic clouds." Further evidence in favour of the "eddy-motion" theory is

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[*] REYNOLDS, 'Royal Soc. Proc.,' 22, 1874, p. 531; or 'Scientific Papers,' vol. i., p. 89.

[†] MALLOCK, A., "Note on Wind Velocity and Gusts," 'Technical Report of the Advisory Committee for Aeronautics,' 1912-13, Report No. 93, p. 329.

[‡] TAYLOR, G. I., "Eddy Motion in the Atmosphere," 'Phil. Trans.,' 215 A., pp. 1-26.

[§] DINES, J. S., 'Technical Report of the Advisory Committee for Aeronautics,' 1911-12, pp. 213-230; 1912-13, pp. 310, *et seq.*

[||] The writer is indebted to Mr. TAYLOR for communicating these results by letter and for permission to mention them here prior to the publication of his paper on the subject.

discussed in detail in connection with the Father Point observations described in Appendix II.

(ii.) *Discussion of the Father Point Acoustic Surveys.*

By the use of the Webster phonometer it was found possible to measure from day to day the amplitude of the sound-waves in the neighbourhood of the Father Point fog-signal station, thus obtaining a permanent record of variations in conditions of propagation depending on meteorological conditions as far as the latter could be observed. In many respects this station was extremely well suited to the work in hand. The surrounding country for several miles is very flat and low-lying, thus reducing to a minimum the effect of local topography on the propagation of sound at sea. The existence of a permanent meteorological station at this point, together with good wharfage facilities, proved to be very convenient in carrying out the acoustic surveys.

An inspection of the charts reproduced in Appendix II. indicates at once that wind is by far the most important factor in interfering with the propagation of sound. This is especially marked when the wind velocity exceeds 25 miles an hour. On August 25, 1913, on a course bearing N. from the fog-signal station the sound was lost completely at 8500 feet, the wind blowing from the west with a speed of about 25 miles an hour. On calmer days, with the wind in the same quarter, the signals will easily carry three or four times this distance.

The more important features relating to the influence of wind and eddy-motion on the propagation of sound are pointed out in Appendix II. The curious undulatory character of many of the amplitude gradients (in particular that shown in Chart No. 4, August 30, 1913) may be adduced as evidence of a tolerably regular eddy-structure of the atmosphere. The effect of the wind on the propagation of sound according to the evidence detailed in Appendix II. may be summed up as follows:—

(1) A breeze blowing in the direction of the shore line gave rise to the most unfavourable conditions of sound propagation (Charts 8, 9 and 10); somewhat less unfavourable is an off-shore breeze (Chart 7). These conditions may be so unfavourable as to counteract the propitious effect of a breeze blowing in the direction of sound propagation. During the daytime a shore-line breeze is the seat of noticeable temperature fluctuations which probably assist a very irregular eddy-structure in destroying the sound. An off-shore breeze may owe its destructive character in part to an eddy-formation accentuated by the irregular character of the land (trees, buildings, &c.), and, to a greater extent, in the writer's opinion, to the turbulent character of the atmosphere on the leeward side of the fog-alarm building, in the immediate vicinity of the diaphone trumpet.

(2) A breeze blowing shorewards gives rise to comparatively favourable conditions of sound propagation (Charts 5 and 11). This is apparently due to the regular eddy-structure and temperature homogeneity of a wind which has blown over

a large expanse of water.* When, in addition, the direction of the wind is in the direction of sound propagation, we have the most favourable conditions of audibility. Unfortunately, such conditions are, as a rule, not available to ships at sea. Herein lies the probable explanation of the statements made by inhabitants of the country surrounding a fog-signal station, that the range of audibility is, on the average, considerably greater over the land than it is over the sea, in spite of the directive effect of the diaphone trumpet and of the obstructing effect of the fog-alarm buildings on the landward side.

(iii.) *Note on Atmospheric Losses.*

In order to obtain a rough estimate of energy losses in the atmosphere, phonometer observations were taken over a series of circular courses having the fog-signal station as centre. The results are shown graphically in Charts 6, 9, 12, 13, and 14, and are analysed in detail in Appendix II., Table I. The flux of energy in the sound-waves across portions of spheres of different radii subtending the same solid angle at the diaphone is calculated in C.G.S. units. From a knowledge of the acoustic output as determined in Appendix III., we may estimate the energy flux which should be contained in the same solid angle under ideal conditions of propagation. The results seem to indicate that a large proportion of the atmospheric losses occur at no very great distance from the diaphone trumpet. Once the sound has penetrated beyond a radius of about 3000 feet, it will continue to travel on a fairly calm day (wind not greater than 3 miles per hour) with comparatively little loss. In some cases the observations show that at greater distances the sound may be actually reinforced by contributions arising from reflections or refractions from the upper regions of the atmosphere, and to some extent, possibly, by the sound scattered by atmospheric eddies reaching the observer from all directions.

In future studies of losses occurring in the immediate neighbourhood of a fog-signal station, the influence of the buildings in setting up eddy-motion near the siren trumpet with the wind in certain quarters should be kept in mind. A typical case of the atmospheric disturbance to leeward of a building is described by DINES† in a paper on "cliff eddies."

(iv.) *Note on the Effect of Fog.*

According to the verdict of the 1873 South Foreland tests, it would appear that the passage of sound through the atmosphere is not impeded by fog, or by falling snow, hail, or rain. No fog occurred during the Trinity House experiments conducted at St. Catherine's Point in 1901. It is easily understood that the passage of sound may be favoured by the comparatively calm and homogeneous condition of the

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* The Gulf of St. Lawrence is about 25 miles wide in the neighbourhood of Father Point.

† DINES, J. S., "Fourth Report on Wind Structures," 'Technical Report of the Advisory Committee for Aeronautics,' 1912-13, p. 325.

atmosphere usually met with in foggy weather. When the fog lies over the sea in the form of low-lying, distinctly separated banks, as is often the case in the Gulf of St. Lawrence, conditions are very different. In these circumstances it has been pointed out by CATFORD[*] as a result of five years' observations that "when both fog-signal and observer are immersed in the *same* bank of fog, little interference may be expected: if the fog-signal is in fog, and the observer in clear atmosphere, or *vice versa*, great interference may be expected, still more so if the signal is in one fog-bank with the observer in another bank; a bank of fog will often reflect sound very strongly and definitely."

The influence of fog particles on the passage of sound has been studied theoretically by SEWELL,[†] who found that a fog containing 10^6 particles per cubic centimetre having diameters as small as 0·002 mm. would not interfere appreciably with the propagation of waves of small amplitude over the ordinary range of frequencies.

Although preparations were made to navigate during a fog, no opportunity occurred of carrying out an acoustic survey under these conditions during the entire series of Father Point tests. It has been repeatedly asserted to the writer by lighthouse-keepers and others that the sound of a diaphone as heard at a moderate distance (within 1000 feet) seems to be very appreciably stifled. On the only occasion that fog occurred this conclusion was confirmed by the writer as judged by ear. Before the phonometer could be set up to test the point objectively, the fog lifted, and no occasion of carrying out further investigations presented itself subsequently. It is not impossible, in the case of very intense waves in the immediate vicinity of the diaphone trumpet, that a heavy fog may give rise to a marked extinction through its effect on the viscosity, thermal conductivity, and specific heat of the atmosphere. From what has already been said on the subject of the propagation of waves of finite amplitude, it is easily seen how a change in the physical properties of air occasioned by the presence of fog[‡] may be the cause of increased energy losses associated with the propagation of waves of large amplitude. The existence of such losses may not be inconsistent with better audibility at a great distance, resulting from propagation under conditions of improved atmospheric homogeneity generally prevailing in foggy weather.

(v.) *Note on the Determination of the Direction of Sound.*

It is important that the navigator be able to ascertain as accurately as possible the bearing of a fog-alarm from the signals which he hears. From what has already

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[*] CATFORD, E. O. (Engineer-in-charge of the Platte Fougère Fog-signal Station, Guernsey), "Fog Signals," 'Engineer,' 119, Feb. 5, 1915, pp. 129–130.

[†] SEWELL, C. J. T., "The Extinction of Sound in a Viscous Atmosphere," &c., 'Phil. Trans.,' 210, A, 1910, pp. 239–270.

[‡] A study of the physical characteristics of fog has recently been commenced by WELLS, P. V., and THOMAS, A. L., 'Bulletin No. 5 of the International Ice Observation and Ice Patrol Service,' U.S. Treasury Department, Washington, 1916.

been said regarding the existence of echoes from fog-banks and from atmospheric eddies, it will be realized that this is often a matter of some difficulty. The writer has often observed that after a second or two from the moment that a signal is first heard the sound appears to reach the observer from every direction, in many cases before his attention can be fixed to determine its bearing. A peculiar characteristic of the diaphone signal which differentiates it from that of a ship siren is a short and powerful terminal note of diminishing pitch caused by the slowing down of the piston for a few oscillations at the end of a blast. This terminal note (or "grunt," as it is called at sea), being of longer wave-length, not only travels with less attenuation, but is easily distinguished from the reflections or echoes of the first part of the signal. Owing to its short duration it does not overlap its own echoes. Navigators make use of the first part of the signal as a "stand-by," and depend on the terminal "grunt" for fixing direction. If a signal consists of two or more blasts, the bearing of the fog-alarm may be determined in this way with considerable accuracy. The peculiarity of the diaphone note just mentioned was an unexpected development and is emphasized in modern installations.

§ 13. ON THE THERMODYNAMIC MEASUREMENT OF ACOUSTIC OUTPUT.

(i.) *Experimental Arrangements.*

In view of the fact that the sound-waves in the immediate neighbourhood of a fog-signal generator are probably propagated as waves of finite amplitude with heavy transmission losses, it was necessary to develop a method of measuring the actual proportion of power converted into sound which would be independent of the theory of the propagation of waves of small amplitude and of propagation according to the law of inverse squares.

The principle of the method which was designed to accomplish this purpose may be briefly stated as follows. Imagine two thermometers inserted, one in the high-pressure side, the other in the side open to the atmosphere, of a siren or other sound-producing instrument operated by compressed air. If the air be allowed to escape without producing sound, there will be no fall of temperature as no external work is done by the escaping air (except for the negligibly small Joule-Thomson effect; the thermometers are supposed to be situated in regions of steady flow, free from eddy-currents). If, now, the siren is allowed to sound, the rate of escape of air being regulated to the same value as before, the low-pressure thermometer will register a fall of temperature, and the difference of the two thermometer readings will give a measure of the external work propagated to a distance as sound according to the theory developed in § 6.

A reference to fig. 3 will indicate the general arrangement of the apparatus. Two resistance thermometers were constructed of fine silk-covered iron wire, wound inside a brass framework and held in position by loops of silk thread; the construction is illustrated in Plate 1 (iv.) and is described in further detail in Appendix III. The open network formed by the iron wire gave a thermometer of minimum heat-capacity and very small lag. One of these was designed to fit into the large operating-valve of the diaphone, while the other was inserted in the resonator a few inches from the diaphone-piston. The resistance thermometers were connected to form the adjacent arms of a Wheatstone bridge and were thus operated differentially. In measuring a difference of temperature during a blast a rough setting was made on the bridge wire in the neighbourhood of the balance point, and the final reading was obtained in terms of the galvanometer-deflection previously calibrated in bridge-wire units. As the capacity of the air-compressing machinery only allowed of a six-second blast per minute, it was essential that the wire of the thermometer take up its final temperature in this interval; this was verified by noting that the galvanometer deflection attained to a steady value during the last three seconds of blast. The difference of temperature θ (θ = (valve-temperature)−(resonator-temperature)) was measured for a certain pressure and air consumption while the diaphone was emitting a note; the piston of the diaphone was then stopped and so adjusted that for the same pressures the air consumption remained the same as before, while the temperature difference θ' was measured under the new conditions. It is a well-known thermodynamical principle, experimentally tested in the celebrated Joule-Thomson porous-plug experiment,* that when air under pressure is allowed to escape and no external work is done, there is no difference of temperature except for the small Joule-Thomson effect arising from the work done in separating molecules under

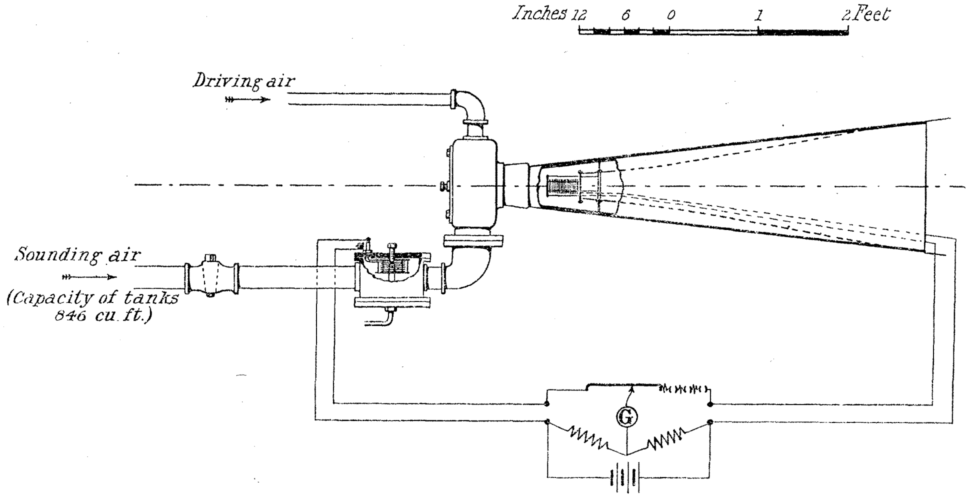

Fig. 3. Determination of acoustic output of Father Point diaphone.
Diagram showing the position of iron-wire resistance thermometers for measuring temperature difference of air on high and low pressure side of diaphone piston.

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* JOULE AND THOMSON, "On the Thermal Effects of Fluids in Motion"; KELVIN, 'Collected Works,' vol. I., p. 333.

conditions of feeble intramolecular attractions. The experimental conditions for realizing this result is that the two thermometers be placed in regions of flow sufficiently distant from the jet that all eddy-motion has disappeared and the equivalent kinetic energy of mean-motion has been degraded by the action viscosity into mean thermal molecular agitation, *i.e.* into heat returned to the gas.

(ii.) *Sources of Error in the Measurement of Temperatures.*

In the case of the diaphone the energy propagated away as sound must be included as external work done by the air under compression, and there will result a corresponding drop in temperature between the pair of differential thermometers. In the actual experiment it was not possible to place the thermometers in regions free from eddy-motion. Moreover, the velocity with which the air stream impinges on the wires of the thermometer (velocity about 42 metres/sec.) is sufficient to cause a slight rise of temperature, although this source of error is eliminated to a considerable extent by the differential arrangement. The rises of temperature due to this cause are included in the differential temperature measurements θ and θ', and are denoted, when the siren is sounding and silent, by $\delta\theta$ and $\delta\theta'$ respectively. By adopting the method of taking temperature readings with the siren sounding and silent, the source of uncertainty due to the effect of "kinetic heating" is reduced to a minimum.

Let $\dot{w}+\dot{f}$ represent the rate at which the energy of the compressed air is converted into mechanical effect in the diaphone when sounding. We then have, by a slight extension of (44),

$$\dot{w}+\dot{f} = \mathrm{JC}_v\dot{\mathrm{M}}\,(\theta-\Delta\theta). \quad \text{. . . . .} \quad (55)$$

In this equation $\dot{w}$ is the rate at which energy is propagated away as sound in ergs/sec. and $\dot{f}$ includes rate at which energy is converted into vis-viva of eddy-motion in the region where the temperature difference θ is observed, plus the rate at which energy is dissipated by thermal conduction into the diaphone piston. The temperature difference due to the Joule-Thomson effect is denoted by $\Delta\theta$; C_v is the specific heat of air per unit mass at constant volume and $\dot{\mathrm{M}}$ is the total rate of air consumption in grammes/sec. If we denote by accented letters the corresponding quantities referring to a measurement of temperature-differences carried out in the same way with the diaphone silent and adjusted so that the air consumption $\dot{\mathrm{M}}$ remained the same at the same pressures, we have $\dot{w}' = 0$, since there is no external work done as sound. Thus

$$\dot{f}' = \mathrm{JC}_v\dot{\mathrm{M}}\,(\theta'-\Delta\theta'). \quad \text{. . . . .} \quad (56)$$

From (55) and (56) we obtain

$$\dot{w} = \mathrm{JC}_v\dot{\mathrm{M}}\,[(\theta-\theta')-(\Delta\theta-\Delta\theta')]-(\dot{f}-\dot{f}'). \quad \text{. . . . . . .} \quad (57)$$

The extent to which the right-hand side of (57) may be taken to represent the energy propagated away as sound depends on how far we may identify the term $\dot{f}'$

for steady flow with $\dot{f}$ in the case of intermittent flow. If it is ascertained that the eddy-motion has entirely disappeared over the regions where the temperatures are measured, $\dot{f}$ and $\dot{f}'$ are steadily converted into heat given up to the gas and are then included in the terms of (57) depending on θ and θ'; the same remark applies to the parts of $\dot{f}$ and $\dot{f}'$ representing thermal energy given up to the diaphone piston. The practical realization of this condition would be to place the resonator-thermometer sufficiently far from the piston that the escaping air is free from eddies. The objection to this procedure lies in the fact that losses of heat into the material of the trumpet are liable to be involved, and also that owing to possible propagation losses the acoustic output is no longer measured at the source of the sound-waves, but becomes a function of the dimensions, shape, &c., of the resonator. It is evident that unless $\dot{f}'$ can be identified with $\dot{f}$, the value of $\dot{w}$ calculated from (57) will be an over-estimate (the case $\dot{f}' < \dot{f}$ is hardly probable).

The temperature differences calculated from the readings of the resistance thermometers, denoted by θ_1 and θ'_1, differ from the true temperature differences θ and θ' by amounts $\delta\theta$ and $\delta\theta'$ respectively, arising from the effect of kinetic heating already mentioned. Although this effect is diminished owing to the fact that differential readings of temperature are taken, the resonator thermometer registered an excess of temperature over the valve thermometer owing to the fact that the former was more exposed to air velocity than the latter. Writing $\theta_1 = \theta - \delta\theta$ and $\theta'_1 = \theta' - \delta\theta'$, equation (57) becomes

$$w = \mathrm{JC}_v\dot{\mathrm{M}}(\theta_1-\theta'_1)+\mathrm{JC}_v\dot{\mathrm{M}}[(\delta\theta-\delta\theta')-(\Delta\theta-\Delta\theta')]-(\dot{f}-\dot{f}'). \quad . \quad . \quad . \quad (58)$$

It is not unreasonable to assume that the Joule-Thomson effect is very approximately the same for steady as for intermittent flow, so that the term $(\Delta\theta-\Delta\theta')$ in (58) may be neglected.

More serious is the kinetic effect due to the air impinging on the wires of the resistance thermometers. The term $(\delta\theta-\delta\theta')$ can only be neglected if this effect is approximately the same for steady as for intermittent flow. The effect of the silk insulation on the wires is in favour of reducing this effect by confining periodic temperature changes to the surface in a manner analogous to the well-known skin effect in the electrical conduction of alternating currents. A rough estimate of this source of error may be made as follows :—

According to the experiments of JOULE and THOMSON* it was found that the rise of temperature due to kinetic heating in a steady air current of velocity U was proportional to the square of the velocity. In the case of the insulated thermometer wires, we may write for the rise of temperature at the surface of the insulation the expression

$$\theta_s = \kappa \mathrm{U}^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (59)$$

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* JOULE and THOMSON, 'Trans. Roy. Soc.,' June, 1860; KELVIN, 'Collected Works,' vol. I., p. 405.

When the velocity is intermittent we may write for the purpose of the present discussion

$$U = U_0(1+\epsilon\cos pt) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

where U_0 is the average velocity of the air, and $|\dot{\xi}| = \epsilon U_0$ may be taken to represent the velocity amplitude in the sound-wave generated by the intermittent flow. From (59) and (60) we have for the surface temperature the expression

$$\theta_s = \kappa U_0^2(1+\tfrac{1}{2}\epsilon^2+2\epsilon\cos pt+\tfrac{1}{2}\epsilon^2\cos 2pt).$$

At the surface of the iron thermometer wire (radius of silk insulation = 0·0092 cm., radius of wire = 0·0048 cm.) the periodic terms contribute corresponding fluctuations of much diminished amplitude, which, however, vanish on averaging with regard to the time over a complete period. Thus the average temperature rise due to kinetic heating measured by the thermometer wire is given by

$$\bar{\theta}_i = \kappa U_0^2(1+\tfrac{1}{2}\epsilon^2). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

Denoting by the suffixes $_v$ and $_r$ temperatures of the valve and resonator thermometers respectively, we notice that $\delta\theta$ of equation (58) is the difference of the temperature rises due to kinetic heating, so that we may write

$$\delta\theta = \bar{\theta}_{iv}-\bar{\theta}_{ir} = \kappa_v U_{0v}^2(1+\tfrac{1}{2}\epsilon_v^2)-\kappa_r U_{0r}^2(1+\tfrac{1}{2}\epsilon_r^2).$$

When the diaphone is silent and the average flow is the same we have, writing $\epsilon_v = 0$ and $\epsilon_r = 0$

$$\delta\theta' = \kappa_v U_{0v}^2-\kappa_r U_{0r}^2,$$

and thus

$$\delta\theta-\delta\theta' = \tfrac{1}{2}\kappa_v U_{0v}^2\epsilon_v^2-\tfrac{1}{2}\kappa_r U_{0r}^2\epsilon_r^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

If we take the value of $|\dot{\xi}|$ obtained in (64) from the measurements of the acoustic output of the diaphone, we have $|\dot{\xi}| = 3·02\times10^3$ cm./sec. corresponding to an average velocity $U_0 = 4·18\times10^3$ cm./sec., and hence $\frac{1}{2}\epsilon_r^2 = \frac{1}{2}|\dot{\xi}|/U_{0r})^2 = 0·26$.

The term $\kappa_r U_{0r}^2$ represents the kinetic heating effect of a stream of velocity U_{0r} in the resonator. The experiments of KELVIN and JOULE already quoted give the rise of temperature due to this cause as 1° C. for 180 ft./sec. ($5·48\times10^3$ cm./sec.). Thus the value of the second term on the right-hand side of (62) is given by $0·26\times[(4·18)/(5·48)]^2\times1°$ C. = 0·15° C. As it is probable that the first term on the right-hand side of (62) is of a magnitude not very different from that just calculated, we are justified in supposing the term $(\delta\theta-\delta\theta')$ in equation (58) to be small compared to the principal term $(\theta_1-\theta'_1)$.

Under the assumptions just made, we may write, finally, in terms of the temperature difference obtained from the readings of the differential resistance thermometers,

$$\dot{w} = JC_v\dot{M}(\theta_1-\theta'_1)\text{ ergs/sec.} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

This result enables us to calculate the rate at which energy is being propagated away as sound, and hence, in conjunction with equation (45), gives us a measure of the acoustic efficiency of the diaphone measured at the vertex of the conical resonator. As the method is not entirely free from sources of error inherent in the temperature measurements, the efficiency thus determined will be referred to as the "apparent efficiency." As far as can be judged these sources of error are for the most part eliminated by taking temperature differences with the diaphone sounding and silent, so the apparent efficiency is probably not very different from the true value.

(iii.) *Discussion of the Father Point Tests.*

The observations described under Appendix III. were taken on a diaphone actually in service so that no alterations could be made in the disposition of the apparatus to allow of the realization of the most satisfactory conditions for carrying out the tests. The results derived therefrom must, therefore, be regarded as the best available under the circumstances. The characteristics of the diaphone are shown graphically in figs. (i.) to (iv.) of Appendix III. It is interesting to notice that the acoustic efficiency is at a maximum at an operating pressure of about 20 lbs. per square inch, not very different from that at which fog-signal engineers have found by experiment that the note is most smooth and penetrating. It may be inferred from the trend of the curves that at very low pressures the acoustic efficiency would probably be of the order of one or two parts in a thousand, as has been found by WEBSTER to be the case for musical wind instruments operated by air at a pressure of a few inches of water.

The conditions under which sound-waves are generated by the alternate opening and closing of the ports in the diaphone piston are too complex to allow of an estimate being made of the wave-form in the resonator. This aspect of the subject should, however, be dealt with experimentally by the oscillating valve method. We are unable at the present moment to understand definitely the part played by the formation of the discontinuity in preventing a greater proportion of energy to be propagated to a distance as sound-waves. In its application to fog-signal waves, the problem is greatly complicated by propagation in three dimensions, the divergence tending to retard the tendency to the formation of a discontinuity with the resulting dissipation of energy. The effect of confining the sound-wave to a conical trumpet tends to enhance the formation of a discontinuity. The superiority of the short trumpets employed in practice would seem to be due to the fact that conditions are so adjusted that, while the advantage of resonance is obtained, discontinuity does not form before the wave has emerged into the free atmosphere, when more rapid divergence precludes the further possibility of discontinuity taking place. The fact that in a siren the wave is carried forward by air moving with considerable velocity would tend to retard the formation of the discontinuity and probably increase the power delivered to the free atmosphere. All these questions are of great importance in practice and constitute a practically unexplored field for future investigation.

Some light may be thrown on the formation of the discontinuity by considering a harmonic plane wave propagated in a cylindrical tube having the cross-section (90 cm.^{2}) of the narrowest part of the conical resonator of the diaphone whose acoustic output was measured by the thermodynamical method. It will be noticed from Test 3 that the maximum power output is 2·36 H.P. at a pressure of 19·1 pounds per sq. in.* The air consumption is 13·3 cubic ft. per sec., which gives for the mean velocity of air over the 90 cm.^{2} cross-section of the resonator the value $4{\cdot}18 \times 10^3$ cm./sec. at the frequency $n = 175$. If we assume that the wave is initially harmonic (an assumption which sets a lower limit to the maximum compression) we may estimate the numerical characteristics of the equivalent sine-wave from the formulæ of § 1. We have $[d\mathrm{W}/dt] = 2{\cdot}36 \times 746 \times 10^7/90 = 1{\cdot}95 \times 10^8$ ergs cm.$^{-2}$ sec.$^{-1}$. Taking $a = 3{\cdot}32 \times 10^4$ cm./sec., $\rho_0 = 1{\cdot}29 \times 10^{-3}$ gr./cm.^{3}, we obtain $a\rho_0 = 42{\cdot}8$.

In terms of the pressure amplitude we have from formulæ (7) $|\delta p|^2 = 2a\rho_0 [d\mathrm{W}/dt]$, giving

$$\left.\begin{array}{ll} |\delta p| = 1{\cdot}29 \times 10^5 \text{ dynes/cm.}^2, & |\dot{\xi}| = 3{\cdot}02 \times 10^3 \text{ cm./sec.} \\ |\xi| = 2{\cdot}74 \text{ cm.} & |\delta\rho|/\rho_0 = |s| = 0{\cdot}091 \end{array}\right\} \quad . \quad . \quad (64)$$

According to formula (23) we are enabled to calculate that the distance x_1 which the wave will travel before discontinuity sets in, by identifying U of that formula with the above value of $|\dot{\xi}|$. We thus find, for $\gamma = 1{\cdot}40$,

$$296 \text{ cm.} < x_1 < 327 \text{ cm.}$$

The estimate just derived leads the writer to believe that in actual fog-alarms the tendency to the formation of a discontinuity in a distance comparable to the wave-length and to the axial length of the resonator plays an important part in determining the output of sound which is eventually transmitted to a distance.

§ 14. SUMMARY AND CONCLUSIONS.

The tests described in the present paper have demonstrated the successful use of the Webster phonometer as a simple and practical instrument for the measurement of the characteristics of pure-toned sound-waves of ordinary intensity. By carrying out acoustic surveys with this instrument, the propagation of fog-signal waves under varying conditions of wind and weather has been studied. The observations show that the wind is by far the most important factor affecting sound propagation. Many of these results may be interpreted in terms of TAYLOR's theory of extinction of sound by the eddy structure of the atmosphere. From this point of view it may

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* [*Added February* 14, 1919.—From phonodeik records taken during the 1917 tests at 860 feet distance it was estimated that 25 per cent. of the total acoustic output is contained in the master tone of pitch 174. See footnote, p. 247.]

be expected that further work with the Webster phonometer will contribute materially to our knowledge of atmospheric structure.

By examining the distribution of sound along circular arcs at different distances from the source it is concluded that the greater part of the atmospheric losses occur within half-a-mile, and very probably within a few hundred feet of the siren trumpet. To measure the very intense sound-waves at this close range a less sensitive phonometer without a resonator is recommended for future work. The acoustic wave-form within the trumpet itself should be studied in connection with the theory of the propagation of waves of large amplitude. Theory shows that, in an ideal medium, plane sound-waves transmitting only a small fraction (from 5 to 8 per cent.) of the energy available as compressed air across the area of the narrowest part of the trumpet could only travel about 10 feet before discontinuity sets in. In reality, the tendency to form a discontinuity will be retarded owing to the effect of viscosity and thermal conductivity and owing to the divergence of the waves in three dimensions. It is suggested, however, that the serious energy losses known to exist in the conversion of energy of compressed air into sound may be closely associated with phenomena of finite wave propagation. The experimental solution of this problem will be necessary before we are able to ascertain whether there is any limit (as in the case of ordinary heat engines) to the proportion of power capable of being converted into sound.

In order to obtain some preliminary information on this question, of considerable practical importance in the design of fog-signal generators, the acoustic output of the diaphone was estimated by measuring the difference of temperature of the air on the high- and low-pressure side. Specially wound resistance thermometers of minimum heat capacity enabled temperature differences to be measured to 1/100° C. This temperature difference is a measure of the external work done by the compressed air, propagated away as sound. By means of a few simple thermodynamical formulæ the acoustic output may be calculated in terms of this temperature difference. It was found that under the best conditions nearly two and a-half horse-power may be delivered by the diaphone as sound. In rating the efficiency of the diaphone it was necessary to adopt a standard of comparison. That chosen was an ideal siren operating on an adiabatic cycle and capable of converting (in some way as yet undiscovered) *all* the energy of compressed air into sound. In these terms the acoustic efficiency of the diaphone under the best conditions came out to be a little over 8 per cent. It is probable that the larger and more modern types of diaphones have acoustic efficiencies considerably greater than the above figure. The estimates of acoustic output obtained in these experiments must, therefore, be regarded as provisional, pending further work on the subject.

There remains the pleasant duty of acknowledging valuable assistance and co-operation from many quarters. The writer is much indebted to Prof. A. G. WEBSTER, of Clark University, for his kindness in undertaking to supervise the construction of a "phonometer" specially designed for the Father Point tests, and also for placing at the writer's disposal the manuscript of a memoir dealing with the mathematical theory of his sound-measuring instruments. To the Postmaster-General of Canada, the Hon. L. P. PELLETIER, the writer is indebted for permission to take up permanent quarters on board the mail tender, "Lady Evelyn," stationed at Rimouski, and to make use of this ship in carrying out acoustic surveys in the neighbourhood of the Father Point signal station a few miles away. The writer wishes to testify to the unfailing courtesy of Capt. J. B. POULIOT and officers of the "Lady Evelyn" in carrying out these tests, and their willingness to co-operate in bringing them to a successful conclusion. For the loan of surveying instruments and valuable assistance in constructing charts of the locality, the writer wishes to thank Commander C. SAVARY of the Hydrographical Survey Ship "Cartier." To Mr. H. H. HEMMING the writer is indebted for invaluable assistance in taking observations during the entire month during which the experiments lasted.

Finally, the writer wishes to express his deep obligation to Prof. H. T. BARNES, F.R.S., Director of the Macdonald Physics Building, not only for placing the resources of the laboratory at his disposal for the work, but in kindly offering to bring to the attention of the Canadian Government the importance of this field of research. As a result, facilities for carrying out the tests at Father Point were generously provided for on a very liberal scale by the Department of Marine and Fisheries.

[*Note added February* 14, 1919.—Fog-signal tests were carried out at Father Point in September and October, 1917, under the auspices of the Canadian Honorary Advisory Council for Scientific and Industrial Research. A detailed account of the results obtained is to be published in a Report, copies of which may be obtained from the Secretary of the above Council, Department of Trade and Commerce, Ottawa, Ontario.

In the course of these tests a thorough investigation was made of the thermal method of measuring the acoustic output of a small diaphone sounding a continuous blast. Temperature differences were measured by means of a pair of thermo-elements inserted, one on the high-pressure side of the vibrating piston, the other on the low-pressure side. Almost continuous temperature readings were recorded as the air-pressure was allowed to fall gradually from 29 to 6 pounds per square inch; the corresponding acoustic outputs were found to be 350 and 100 watts respectively, while the acoustic efficiencies were eight per cent. at the higher pressure and 24 per cent. at the lower pressure. Several series of observations with and without the trumpet confirmed these results which, taken in conjunction with those obtained from the 1913 tests on a large diaphone, indicate that higher efficiency and greater atmospheric penetration in fog-signal apparatus may be predicted by the utilization of low air-pressures and by the separation of a single source of sound into a number of small synchronized units.

With the co-operation of Prof. DAYTON C. MILLER of the Case School of Applied Science, Cleveland, Ohio, U.S.A., notes from the large and small diaphones were recorded in permanent form as sinuous lines on photographic films, making use of the "phonodeik," a description of which will be found in the inventor's recent book "The Science of Musical Sounds," (Macmillan & Co., New York, 1916). Records were obtained to distances of nearly three miles, and their analysis brought out a number of interesting and important facts. It was found that the sound from the small diaphone, provided with a detachable trumpet, was extremely complex. From records taken with and without the trumpet, it was inferred that the effect of a resonator of correct design would be to concentrate a greater proportion of the total acoustic output into the master tone. The records obtained at various distances from the large diaphone indicate that the high overtones do not travel far, but are filtered out by the scattering action of atmospheric eddies. As the master tone alone survives to an appreciable extent at distances greater than two miles, it is obvious that the object of the designer of fog-signal apparatus should be to concentrate the greatest possible amount of energy into the master tone. From the harmonic analysis of the phonodeik records it is now possible to obtain accurate data as to the relative proportions of energy contained in the master tone and in the overtones.]

APPENDIX I.—ON THE ACOUSTIC CHARACTERISTICS OF THE WEBSTER PHONOMETER AS EMPLOYED IN THE MEASUREMENT OF SOUND FROM THE DIAPHONE.

(i.) DETERMINATION OF PHONOMETER CONSTANTS.

The detailed construction of the Webster phonometer employed during the Father Point tests is briefly described in § 11 and 15 illustrated in fig. 2.

After the instrument had been employed in carrying out the measurements of sound from the diaphone as described in the present paper, the constants of the instrument were kindly determined by Prof. WEBSTER himself at Clark University. Without going very far into the mathematical theory of the phonometer, which is to be considered by Prof. WEBSTER elsewhere, it may be remarked that the free vibrations of the diaphragm may be represented by the differential equation

$$m\ddot{x}+\kappa\dot{x}+fx = 0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(i.)}$$

where m is the effective mass of the loaded diaphragm, κ is the effective damping constant, and f is the effective stiffness of the diaphragm. According to the determination of Prof. WEBSTER

$$m = 0 \cdot 891 \text{ grs.}, \qquad \kappa = 14 \cdot 0 \text{ dynes/(cm. per sec.)},$$

and

$$f = 5 \cdot 67 \times 10^{6} \text{ dynes/cm.}$$

The frequency n of the fundamental, given by

$$2\pi n = [f/m-(\kappa/2m)^{2}]^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(ii.)}$$

gives $n = 401$ complete vibrations per second.

The magnification of the optical system was determined by mounting an interferometer on the resonator side of the mica diaphragm, and by means of a stroboscopic arrangement measuring the displacement of the centre in terms of a wave-length of light while in actual vibration at frequency 175. At the same time the breadth of the luminous band in which the filament was drawn out was read in the usual way. In this way it was found that 1-scale division of the microscope eye-piece (1 mm.) corresponded to 0·000120 cm. diaphragm displacement.

The pressure amplitude in a sound-wave, $|\delta p|$, is connected with the diaphragm displacement and resonator constants by formulæ which have been developed theoretically (and verified experimentally) by Prof. WEBSTER. According to his determinations, with the resonator in position 8, $|\delta p|$ (expressed in dynes/cm.^{2}), is connected with the diaphragm amplitude $|\delta x|$ (expressed in cm.) by the relation

$$|\delta x| = 8 \cdot 48 \times 10^{-5} |\delta p| . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iii.)}$$

Hence if d is the phonometer scale reading (double amplitude in mm.) we have $\frac{1}{2}d \times 0 \cdot 000120 = |\delta x|$, from which it follows that

$$|\delta p| = 0 \cdot 708 \times d \text{ dynes/cm.}^2 . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv.)}$$

Prof. WEBSTER states that the constants from which (iii.) was derived were tested by measuring in the open air the sound from a standard "phone" or sound generator at pitch 256. Agreements were obtained to within less than one per cent.

There are difficulties in the way of applying (iv.), as determined for small intensities, to convert the larger readings (greater than 5 mm.) to pressure amplitudes, owing to the fact that in the latter case noticeable eddies are set up in the neighbourhood of the resonator aperture. For this reason it would be necessary to carry out a special series of experiments to determine the limits of error (if any) involved in measuring very powerful fog-signal waves by means of the phonometer. As the pressure amplitudes in the immediate neighbourhood of a fog-signal generator are very large, there is no need for the magnifying effect of a resonator. In future experiments the difficulty just mentioned may be dispensed with by making use of a phonometer consisting only of a suitable diaphragm together with the optical system for determining its vibration amplitude. On account of these uncertainties the phonometer readings obtained on the various acoustic surveys are not reduced to pressure amplitudes. The recorded readings are, however, comparable among themselves for an instrument built to the exact dimensions of that employed in the present tests. While the phonometer readings at a distance may be accurately converted into pressure amplitudes, the variability of atmospheric conditions, even on a calm day, and the absence of any definite law of propagation make it impossible to utilize absolute readings except to a limited extent. In the tabulation of the observations obtained on the acoustic surveys described in Appendix II., and in their graphic representation in the accompanying charts, the results are given in terms of the phonometer readings, which may be reduced, if required, to pressure amplitudes by formula (iv.).

A glance at the tabulated results of the acoustic surveys show that a phonometer reading of 0·1 mm. corresponds to a signal which is feeble, but still sufficiently distinct to serve as a warning under ordinary conditions prevailing at sea. According to formula (iv.) this corresponds to a pressure amplitude,

$$|\delta p| = 0\cdot 071 \text{ dynes/cm.}^2 = 7\cdot 0 \times 10^{-8} \text{ atmosphere.}$$

It is interesting to note that this is not far removed from the estimate $|\delta p| = 9\cdot 2 \times 10^{-8}$ atmosphere for a just audible note of pitch 181 as determined by TÖPLER and BOLTZMANN.* The sensitivity of the phonometer was thus very suitably adjusted for the purpose of fog-signal testing at great distances.

(ii.) CALIBRATION OF PHONOMETER RESONATOR FOR PITCH.

In order to employ the Webster phonometer in the measurement of sound, it is necessary to tune the resonator to the pitch of the note emitted by the diaphone. This is accomplished by pulling out the inner of the two telescoping cylinders shown in fig. 2, whose position with reference to the outer cylinder is indicated by means of a centimetre scale engraved on the former. Each "resonator position," as defined by the scale reading, corresponds to a definite fundamental pitch. This was determined experimentally by running a small laboratory siren of the usual type by means of compressed air stored up in the tanks of the fog-signal apparatus.† By keeping a finger dipped in oil pressed against the revolving spindle of the siren the speed could be regulated and kept constant over a sufficient length of time to permit the speed of rotation to be accurately determined by means of a stop-watch. At each position of the resonator the siren was allowed to gain in speed while the image of the filament was carefully observed. Resonance was at once observed by widening of the image into a broad band. The siren was then held at this speed and the pitch determined in the usual way. As the pitch was allowed to increase to a value in the neighbourhood of 2000, a whole series of resonance frequencies was observed. There was no difficulty in selecting those corresponding to the fundamental frequencies of the resonator (n complete vibrations per second). It was found that resonance was obtained for frequencies of $\frac{1}{2}n$; this was evidently due to the first harmonic of the complex note emitted by the siren. More difficult to explain were a series of several resonance frequencies unconnected with the resonator pitch in any simple way, but showing evidence of simple numerical relationships among themselves. As it was

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* TÖPLER and BOLTZMANN 'Ann. Phys. Chem.,' 141, 1870, pp. 321–352. BOLTZMANN's estimate is probably a little too great. For a note of pitch 200 WIEN gives $|\delta p| = 1\cdot 0 \times 10^{-9}$ atmosphere (quoted by RAYLEIGH, 'Phil. Mag.,' 14, 1907, pp. 596–604, 'Scientific Papers,' vol. v., p. 420). For a note of pitch 256 WEBSTER gives $|\delta p| = 8\cdot 9 \times 10^{-9}$, agreeing fairly well with the value $|\delta p| = 6\cdot 0 \times 10^{-9}$ obtained by RAYLEIGH for a note of the same pitch.

† The siren is very unsatisfactory for the purpose of this determination owing to the presence in the note emitted of a very large number of high harmonics, whose frequencies may coincide with those of the high-pitched overtones of the diaphragm or of the resonator itself, giving rise to numerous spurious resonances.

suspected that these were in some way connected with the free periods of vibration of the mica diaphragm (loaded at the centre) the resonator chamber and back of the phonometer were entirely removed. It was then found that resonance occurred at the following frequencies:

297, 381, 582, 1141, 2060.

Numbers differing but slightly from these or their sub-multiples could be recognized among the resonance frequencies observed with the resonator in position.* Any note having among its harmonies one of the free periods of the mica diaphragm would show resonance. As the frequencies of these spurious resonances were far removed from that of the diaphone note when sounded over the normal range of air-pressures, the matter was left aside as of subsidiary importance to the main work on hand. In the following table are given the final results of the determinations of resonance frequencies corresponding to the various resonator positions (denoted by h and expressed in centimetres).

TABLE I.

Resonator position. h (cm.).	Frequency. n.	$n^2 \times (h + 10 \cdot 8 \text{ cm.})$.	Resonator position. h (cm.).	Frequency. n.	$n^2 \times (h + 10 \cdot 8 \text{ cm.})$.
0·0	232	$5 \cdot 72 \times 10^5$	6·0	185·5	$5 \cdot 78 \times 10^5$
1·0	224	5·93	7·0	177	5·67
2·0	217·5	6·04	8·0	174·8	5·72
3·0	206	5·85	9·0	168·5	5·62
4·0	200	5·92	10·0	166	5·75
5·0	193	5·88			
				Mean . . .	$5 \cdot 81 \times 10^5$

According to the elementary theory, the resonance frequency of a resonator of volume Q is given by the formula†

$$n = (c/2\pi)\sqrt{(\mathrm{K}/\mathrm{Q})}, \quad \ldots \ldots \ldots \quad (\text{v.})$$

c being the velocity of sound at the temperature of the experiment given by

$$c = c_0(1 + \tfrac{1}{2}\alpha t) = (33130 + 61t) \text{ cm./sec.}, \quad \ldots \ldots \ldots \quad (\text{vi.})$$

where $\alpha = 0 \cdot 00367$ and t is the temperature in degrees C.

K is the "inertia coefficient" or "conductivity" of the aperture; for a circular aperture of radius R in an infinitely extended thin wall $\mathrm{K} = 2\mathrm{R}$.

We may write $\mathrm{Q} = \frac{1}{4}\pi d^2 (h + h_0)$, where d is the diameter of the resonator and h_0 is the mean length of the cylindrical chamber at position 0.

By taking $h_0 = 10 \cdot 8$ cm., we notice from Table I. that the product $n^2(h + h_0)$ is constant within the limits of observational errors, as required by theory. Formula (v.) may then be written

$$n^2(h + 10 \cdot 8) = \pi^{-3}\mathrm{K}c^2/d^2 = 5 \cdot 81 \times 10^5 \quad \ldots \ldots \ldots \quad (\text{vii.})$$

Taking $c = 3 \cdot 40 \times 10^4$ cm./sec. at $t = 15°$ C., $d = 11 \cdot 7$ cm., we derive for K in (vii.) the value $\mathrm{K} = 2 \cdot 12$ cm. The diameter of the aperture of the phonometer resonator was $2\mathrm{R} = 2 \cdot 50$ cm.

The exact theoretical calculation of K for the aperture of a resonator of the type under consideration has not yet been carried out as far as the writer is aware; the above experimental determination shows

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* The resonance frequencies of free edge-clamped diaphragms have been carefully studied by MILLER, D. C., 'The Science of Musical Sounds,' Macmillan and Co., New York, 1916, pp. 148, *et seq.*

† RAYLEIGH, 'Sound' (1896), vol. ii., p. 304.

that it agrees roughly with the value K = 2·50 cm. for an aperture of diameter 2·50 cm. in an infinitely extended thin plate. Reference to fig. 2 of § 11 shows that the length of the resonator at position 0 is not determinate owing to the fact that the face opposite the aperture is not plane. The distance from the mica diaphragm to the aperture is 11·5 cm., not very different from the value of h_0 required to satisfy the theoretical formula (i.). For purposes of approximating to the pitch of such resonators for purposes of design, the theoretical formula (v.) may be employed.

It should be noted that, according to the theoretical formula (v.), the resonance frequency exhibits the same temperature coefficient as the velocity of sound as given by (vi.). In designing an instrument for use in connection with fog-signals, where the temperature is liable to large fluctuations, the resonance should not be too sharp.

The results of Table I. are shown graphically in fig. (i.). The continuous curve drawn through the observed points is calculated according to formula (v.).

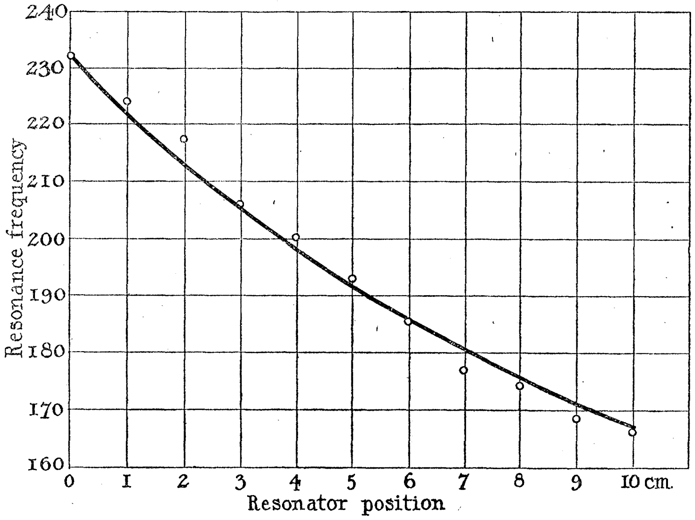

Fig. (i.). Pitch calibration curve of adjustable resonator of Webster phonometer.

(iii.) Determination of Phonometer Resonance Curve with Respect to Sound-Waves Generated by the Diaphone.

At distances from the fog-signal greater than 1000 feet the note of the diaphone appeared to be remarkably pure as far as could be judged by the unaided ear.* At lesser distances, especially within the angle of the resonator, the note was somewhat rougher, while close at hand (50 to 100 feet) a curious crackling sound, somewhat like that emitted when a large sheet of paper is being crumpled up, might be heard at the same time. Behind the resonator, in the acoustic shadow of the fog-signal buildings, the note, while still very loud, was comparatively pure. In order to study the behaviour of the phonometer, with respect to the intense waves emitted by the diaphone, a series of readings was taken at a control station behind the resonator at a corner of the balcony of the fog-signal engineer's residence (marked S in Chart 1 of Appendix II.). The end of the diaphone trumpet was just visible from the phonometer. A few preliminary observations indicated that the diaphone note seemed to have the best quality at a mean pressure (between the beginning and end of the two 3-second blasts) of 19·7 lbs./sq. in. During the entire test the pressure fluctuated very slightly from this value. Readings were taken with the resonator in different positions. In the following table the mean of observations taken on several blasts are given. The maximum readings occurred at resonator position 8·0. According to Table I. the pitch of the diaphone note at the above pressure may be taken at 175 complete vibrations per second. The entire set

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* See footnote, p. 247.

of readings at this position are given to demonstrate the remarkable uniformity of intensity of the successive blasts. The results are shown graphically in fig. (ii.).

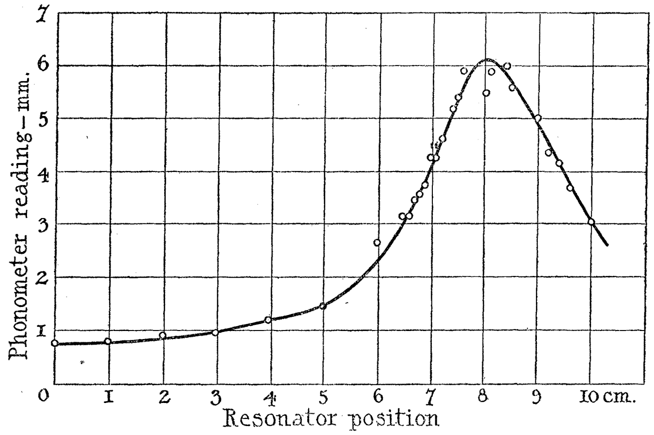

Fig. (ii.). Resonance curve of Webster phonometer with reference to sound-waves generated by the diaphone.

TABLE II.

Resonator position.	No. of observations.	Mean phonometer observations.	Resonator position.	No. of observations.	Mean phonometer observations.	Resonator position.	No. of observations.	Mean phonometer observations.
0·0	1	0·9	6·9	1	3·8	8·4	2	6·0
1·0	1	0·9	7·0	5	4·3	8·5	3	5·6
2·0	1	1·0	7·1	1	4·3	8·8	2	5·6
3·0	2	1·05	7·2	1	4·6	9·0	3	5·0
4·0	3	1·3	7·4	3	5·2	9·2	1	4·4
5·0	4	1·55	7·5	4	5·4	9·4	1	4·2
6·0	4	2·7	7·6	1	5·9	9·6	1	3·7
6·5	1	3·2	7·8	2	5·8	10·0	3	3·1
6·6	1	3·2	8·0	26	5·5			
6·8	1	3·6	8·2	2	5·9			

Successive readings of phonometer with resonator at position 8·0	5·4	5·3	5·2	5·4	6·3	6·2	5·7
	5·4	5·5	5·5	5·4	5·2	6·2	5·5
	5·6	5·7	5·7	5·5	5·2	5·3	
	5·5	5·6	5·5	5·4	5·0	5·1	

AIR Pressures Operating Diaphone.

Beginning of Test.	*End of Test.*
104·5 cm. mercury, falling to 96·5 cm. at end of blast. Mean pressure between blasts, 19·4 lbs./sq. in. above atmospheric.	106·5 cm. mercury, falling to 98·5 cm. at end of blast. Mean pressure between blasts, 19·7 lbs./sq. in. above atmospheric.

According to theory resonance curves obtained in this way for the same frequency, but for signals of different intensities should have their ordinates proportional. It would seem at first sight that for very intense waves the sensitivity of the phonometer could be reduced in the ratio of 6 to 1 by taking readings with the resonator set at a position far removed from that giving resonance. On testing this conclusion for the purpose of employing the phonometer to measure very loud blasts giving readings far off the scale of the instrument when tuned to the exact frequency of the diaphone note, it was found that the proportional relationship did not hold with any approach to accuracy. Although it was surmised that the reason for this discrepancy was connected with the fact that the sound-waves were very much more intense than any which had been hitherto dealt with by means of the phonometer, it was some time before a definite clue was obtained as to the exact nature of the difficulty. While carrying out observations at the control station on a specially calm day, the writer happened to make a slight adjustment of the resonator while a blast was being sounded by the diaphone. A current of air could be distinctly felt blowing outwards from the aperture of the resonator. The phenomenon was investigated with a lighted match which was easily extinguished when held a couple of inches from the resonator. The writer attributes the phenomenon to the formation of a rapid succession of vortex rings set up at the edge of the resonator aperture by the pulsations of air due to the very intense sound-waves (the scale-reading of the phonometer was about 7 mm.). A "vortex stream" is thus set up on both sides of the aperture, that moving into the resonator being broken up and supplying air which issues outwards from the orifice. The phenomenon of jets issuing from resonators has been observed by Lord RAYLEIGH, who has utilized the effect in the design of a "vibration indicator" to measure the powerful sound-waves generated by portable forms of fog-signal apparatus.* It will be evident that for very intense sounds the theory of the absolute phonometer is invalidated to an extent which requires further investigation.

A few tests were carried out to make certain that the readings of the phonometer were unaffected by the direction in which the instrument was pointed with respect to the source of sound. Readings were taken behind the diaphone trumpet at the control station already mentioned, and also at a position about 130 feet from the trumpet on Line VIII. (Chart 1, Appendix II.). Successive readings at intervals of 45 degrees, measured in the direction N.–E.–S.–W., commencing at 0 degrees with the aperture of the phonometer resonator pointed at the diaphone trumpet, are given below.

	0°.	45°.	90°.	135°.	180°.	225°.	270°.	315°.
Control station	6·25	6·3	6·5	6·5	6·5	6·8	6·5	6·5
Position on Line VIII. .	5·5	5·3	5·75	5·6	5·5	—	—	—

The above readings are constant within the limits of accidental fluctuations of amplitude, indicating that neither the azimuth of the resonator axis with respect to the wave-front or the effect of the observer's head has a noticeable effect on the phonometer readings. According to acoustic theory this result is to be expected, as the wave-length (in this case a little over 6 feet) is large compared to the dimensions of the resonator and of the obstacle formed by the observer's head. The result was also verified by similar tests carried out at a distance in a ship's boat as well as from the deck of the "Lady Evelyn," provided in each case the fog-signal station could be directly viewed from the phonometer. This conclusion is of considerable practical importance in the measurement of sound in the open air, as the phonometer may be turned in such a direction as to eliminate the effect of wind which is liable to set up sound vibrations within the resonator when blowing into or across the aperture. Except on very windy days (wind greater than 30 miles an hour) it was found possible to take phonometer readings without difficulty.

(iv.) DETERMINATION OF THE PITCH REGULATION OF THE DIAPHONE.

It has long been known that one of the important features of the diaphone is its extremely good pitch regulation—that is, the remarkably small variation of pitch within wide limits of operating air pressure. In

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* RAYLEIGH, 'Sound' (1896), vol. II., pp. 216–217; 'Phil. Mag.,' VI., 1908, pp. 289–305; 'Scientific Papers,' vol. v., p. 132.

order to obtain an idea of the extent to which the phonometer readings might be affected by variation of pitch, a series of resonance-curves, of the type shown in fig. (ii.), was obtained for a series of operating pressures from 11·7 to 30·5 lbs./sq. in. The phonometer was mounted on a theodolite tripod at position 2, line VII., Chart 1, 100 feet from the diaphone. Here the note of the diaphone was still somewhat rough, indicating the existence of harmonics. While one observer (H. H. H.) operated the fog-signal at the required pressures, the writer took a number of phonometer observations with the resonator at different positions, with a view to determining that giving the maximum reading. As in the tests described in (i.), some cases of spurious resonances were observed, probably due to harmonics coinciding with an upper partial of the resonator or of the diaphragm. There was no difficulty in picking out the particular position of the resonator corresponding to the fundamental frequency of the diaphone note. The final results only are given in Table III. below, and are shown graphically in figs. (i.) and (iii.) of Appendix III. The mean of the pressures at the beginning and end of each 6-second blast is recorded. The position of the resonator corresponding to the maximum phonometer reading was determined from curves corresponding to that shown in fig. (ii.). The pitch of the diaphone note was taken to be that of the phonometer resonator as given by Table I. and the curve of fig. (i.).

TABLE III.

Mean pressure.	Maximum phonometer reading.	Position of resonator at maximum.	Pitch.
lbs./sq. in.	mm.	cm.	
11·7	4·8	9·0	169
15·5	5·3	8·5	171
19·1	8·2	7·7	174
26·9	5·5	6·5	182
30·5	6·3	4·0	200

In carrying out the acoustic surveys described in Appendix II., it was decided to set the phonometer at position 8, corresponding to pitch 175, and to keep the average operating pressure as closely as possible to 20 lbs./sq. in., corresponding to this frequency. From the resonance curve of fig. (ii.), it will be seen that a variation of 1 cm. in the setting of the phonometer resonator between 7·5 and 8·5 cm. will alter the scale-reading by 0·5 mm., from 5·5 to 6·0 mm., which represents, roughly, the limits of variations due to accidental fluctuations in the note emitted by the diaphone. Reference to fig. (i.) shows that this variation of resonator position corresponds to a variation of pitch between 171 and 176. From Table III. above, it will be seen that the pressure operating the diaphone may vary between 16 and 22 lbs./sq. in. before the pitch is altered to this extent. Furthermore, a reference to the results of Appendix III., tests 1 and 3, indicates that the acoustic output, as measured in the diaphone trumpet, does not vary much more than 10 per cent. between 18 and 23 lbs./sq. in. We conclude, finally, that between these limits of pressure the phonometer, with the resonator set in position 8, will give relative measurements of pressure amplitude from day to day to an accuracy within the accidental fluctuations of the signal sounded by the diaphone. Also, provided the phonometer readings are not too large (not greater than 5 mm.), they may be reduced to pressure amplitudes in C.G.S. units by formula (iv.).

(v.) NOTE ON THE QUALITY OF THE SOUND EMITTED BY THE DIAPHONE.

In the Father Point tests of 1913, means were not available for studying the quality of the note emitted by the diaphone. It is evident from the remarks already made that overtones probably exist to some extent in the sound-waves close to the trumpet. Owing to the complex conditions of finite-wave propagation, it is difficult to forecast the relative intensities of the overtones produced in the trumpet from data relating to the characteristics of conical resonators tested in the laboratory.* The form of trumpet actually used (for dimensions see under fig. 1, § 9) was that giving the greatest atmospheric penetration as determined by a large number of trials carried out at Father Point in 1903 under the direction of Lieut.-Colonel W. P. ANDERSON, Chief Engineer of the Canadian Department of Marine and Fisheries. As is well known, the energy of the sound-waves is dissipated largely owing to the effect of eddies in the atmosphere. According to the mathematical theory developed by TAYLOR (discussed in Section 12), the coefficient of extinction is proportional to the square of the frequency. It follows that overtones in the diaphone note will be much more rapidly extinguished than the fundamental. It is thus important in fog-signal apparatus that as much of the acoustic output as possible be concentrated in the fundamental, or "master tone."

The rapid extinction of overtones with increasing distance from the diaphone was repeatedly observed during the tests carried out by the writer. At a distance of about 1000 feet the note was, as far as could be judged by ear, very nearly a pure tone.

The phonometer, when correctly tuned, enables us to measure in C.G.S. units the pressure amplitude in the fundamental, and the readings given in Appendix II. must be interpreted in this way. As regards the carrying power of the signals it is the energy contained in the fundamental which is by far the most important.

It is highly desirable in fog-signal tests that the dependence of attenuation on wave-length be studied in the light of TAYLOR'S theory, and that observations be carried out on the quality of the note at varying distances, as is now possible by the use of MILLER'S "phonodeik."†

APPENDIX II.—ACOUSTIC SURVEYS IN THE NEIGHBOURHOOD OF THE FATHER POINT FOG-SIGNAL STATION.

(i.) GENERAL PROCEDURE IN TAKING OBSERVATIONS.

The object of the acoustic surveys carried out at Father Point was to obtain on different days and under varying meteorological conditions a permanent record of the distribution of sound in the neighbourhood of the same fog-signal station. For this purpose the Webster phonometer described in Appendix I., was found to satisfy the exacting conditions required of a robust and portable instrument sufficiently sensitive to respond to the minute changes of pressure occurring in sound-waves of ordinary loudness.

Through the courtesy of the Department of Marine and Fisheries, permission was given to operate the diaphone at will for the purpose of the tests. Through the kindness of the Postmaster-General, the writer was authorised to take up permanent quarters on the mail tender, "Lady Evelyn," stationed at Rimouski, and to make use of this ship in carrying out acoustic surveys in the neighbourhood of the Father Point signal, a few miles away. Mr. H. H. HEMMING,‡ B.A., assisted in the tests and proved himself invaluable in taking observations. As a matter of regular routine an acoustic survey was carried out whenever possible during the forenoon. The ship was skilfully navigated over a series of courses under the guidance of her commanding officer, Captain J. B. POULIOT. Although the usual weather records were kept at the Father Point meteorological station, it was found necessary, as far as available instruments allowed, to take independent observations from the ship, as air temperatures, wind velocities and directions even half a mile from shore were observed to differ considerably from those on land.

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* As determined by MILLER, D. C., in connection with the development of the "phonodeik." ('The Science of Musical Sounds,' 1916, p. 156, *et seq.*)

† See footnote, p. 247.

‡ Now Capt. H. H. HEMMING, of the Third Field Survey Company, on active service in France.

Air temperature was measured by means of a self-registering thermometer. With the kind permission of Dr. H. T. BARNES, Director of the Macdonald Physics Building, one of his self-recording marine thermometers was installed for the purpose of taking sea temperatures. No direct effect of sea temperatures on sound transmission could be detected, however, so that it has not been thought necessary to reproduce these records. Mr. HEMMING took charge of wind observations with the only apparatus available, a small anemometer consisting of a fan whose revolutions could be timed by means of a stop-watch. With this instrument the velocity of the wind relative to the ship was obtained. The direction of the wind relative to the ship was observed from the direction of the ship's smoke. The ship's speed and the magnetic bearing of the course was noted at the same time. By the usual graphical construction the velocity and direction of the wind relative to the earth's surface was determined. In each of the Charts 1 to 14, the wind velocities at the positions where they were observed are shown in magnitude and direction by arrows, the numbers beside them indicating velocities in statute miles per hour. In future observations of this kind the use of self-registering instruments for wind velocity and direction is recommended.

While phonometer readings were taken at intervals of one minute by the writer, the position of the ship was determined by Mr. HEMMING from sextant observations of the angles subtended by landmarks of known position on shore. Both sets of observations were carefully timed so that the position of the ship at each signal could be plotted down with fair accuracy on a chart of the locality. At each position thus determined an ordinate was drawn perpendicular to the line representing the ship's course, proportional to the phonometer reading, and hence to the pressure amplitude in the wave. In this way is obtained a graphical representation of the variation of sound amplitude along various courses in the neighbourhood of the fog-signal station. It must be kept in mind that the results thus obtained do not represent the state of affairs existing at the same instant, but show variations of amplitude in sequence of time. Each phonometer reading was identified by a position number entered on each of the Charts 1 to 14, opposite the position of the ship at the instant of observation. The corresponding phonometer observations are entered in Tables 1 to 14, together with meteorological observations and remarks.

(ii.) DESCRIPTION OF TABLES AND CHARTS.

No. 1.—*Short Range Acoustic Survey, September* 3, 1913. *Table* 1 *and Chart* 1.

A preliminary survey of conditions of sound propagation in the immediate neighbourhood of the fog-signal station was carried out by means of the Webster phonometer, with a view to obtaining some light on the extent of the large atmospheric losses believed to occur in this region. As a first step, observation stations were marked out at intervals of 50 feet along eight lines radiating from the resonator of the diaphone, making angles of approximately 45 degrees with one another. At the same time topographical observations were carried out, from which a map of the locality could be drawn giving the positions of the various buildings and of the shore line on the seaward side. Observations from which the contour lines of the beach were drawn were carried out by Mr. HEMMING. These are shown in Chart 1 drawn from the data thus obtained. The contour line 1 is the high tide level of September 2, 1913, and is 14 feet below the level of the diaphone resonator. Successive contour lines 1, 2, 3, 4, &c., represent differences of level of 1 foot.

Observations were carried out on September 2, 1913, the day having been chosen on account of the comparatively calm conditions then prevailing. The phonometer was mounted on a theodolite tripod as shown in Plate 1 and tuned to resonator position 8 throughout. The observations were taken almost continuously between 10.30 a.m. and 4 p.m., and are entered in Table 1 in chronological order. Along each of the lines (numbered I. to VIII.) phonometer readings were taken at each observation station and numbered, commencing with No. 1, 50 feet distant from the diaphone: the readings were repeated at each station on the way back. No difficulty was experienced in setting up the phonometer at each station in the 1-minute interval between the blasts. As a rule each of the two 3-second blasts was measured and the mean of the two readings entered. In some cases the readings were repeated for successive blasts. When more than one signal was measured the suffix indicates the number of readings of which the result entered is the mean.

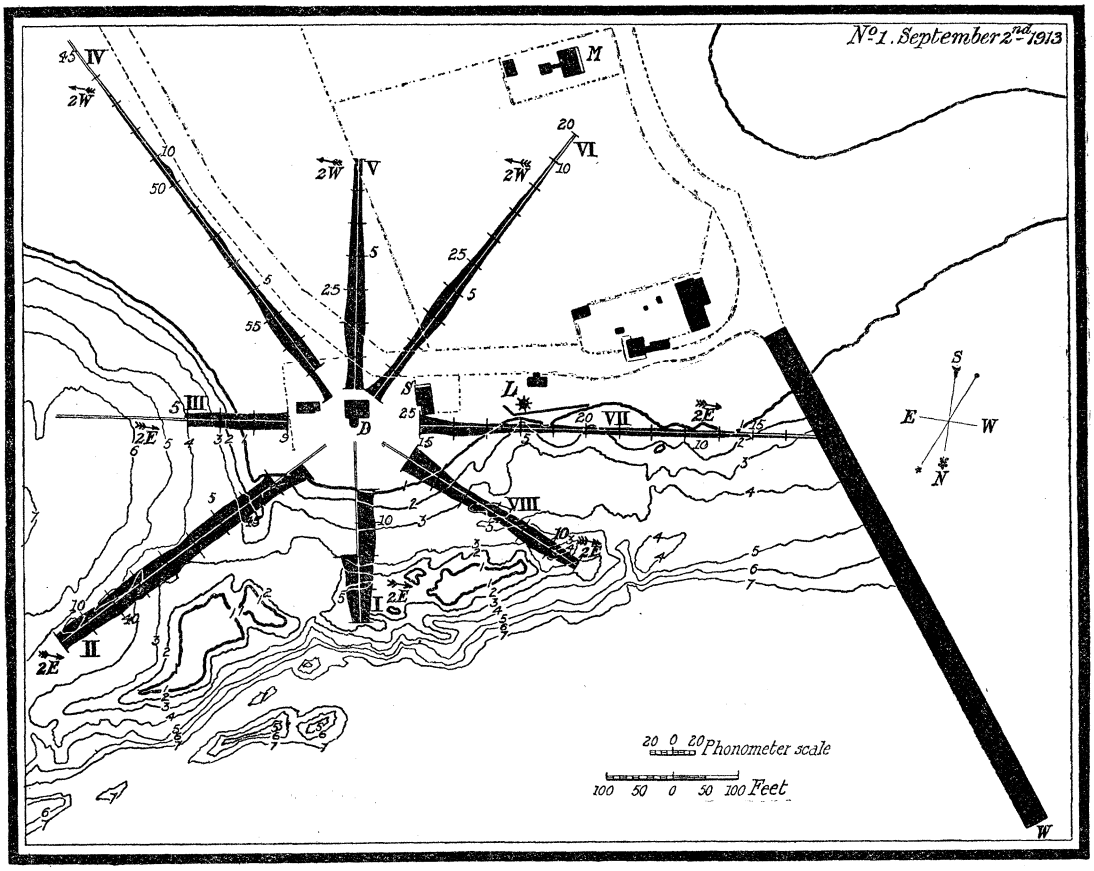


Chart 1. Short range acoustic survey, September 2, 1913. The more important features of the chart referred to in the text are: D, position of the diaphone trumpet; L, Father Point lighthouse; S, control station near engineer's residence; M, meteorological station; W, control station at end of wharf.

The pressure amplitude in the sound-waves was found to be so great within a radius of 100 feet that the phonometer readings were thrown completely off the scale. The readings could be brought on the scale by untuning the resonator. It was found, however, that the resonance curves obtained by plotting phonometer readings against resonator positions (as in fig. (ii.), Appendix I.) did not have proportional ordinates. As the intensity increased, the curves became relatively flatter. A phonometer reading taken with the resonator at any position other than 8 cm., could be expressed in terms of the reading which would be obtained at resonance by a rough interpolation from the series of resonance curves. Such readings, when entered in Table 1, are enclosed in brackets, and are in defect of the true resonance reading if it could have been obtained. As already mentioned under Appendix I., the conversion of the phonometer readings to pressure amplitudes by making use of the constant determined for moderately loud sounds is subject to some uncertainty owing to the existence of eddies in the resonator. Values thus obtained will, however, be in defect of the true pressure amplitude.

The phonometer readings are shown graphically in Chart 1. It will be noticed that although the weather was comparatively calm, atmospheric conditions varied so rapidly that the inward and outward readings taken along each line at intervals of a few minutes are only in rough agreement. There is some reason to believe that a large proportion of the atmospheric losses take place in the immediate vicinity of the fog signal station. It is of considerable importance that the characteristics of the wave-motion be studied in some detail in this region. The results of the acoustic survey just described may be regarded as giving us some preliminary information of conditions to be met with in the design of apparatus especially suited to determining the wave-form and numerical characteristics of waves of large amplitude.

No. 2.—*Short Range Acoustic Survey. September* 4 *and* 5. *Table* 2 *and Chart* 2.

The phonometer observations, entered in Table 2 and shown graphically in Chart 2, were taken from a ship's boat (Plate (ii.)). The position of the boat was determined at each signal by measuring the angles between known landmarks by means of a sextant. The observations extended over two days, September 4 and 5, 1913. Fortunately, wind and weather conditions did not differ greatly on the two occasions. In order to obtain some idea of the relative amounts of sound propagated over sea and land, the observations of September 2 are graphically represented in Chart 2 on the same scale. Attention is drawn to the fluctuating character of the gradients along lines I. and VIII. In both instances we have examples

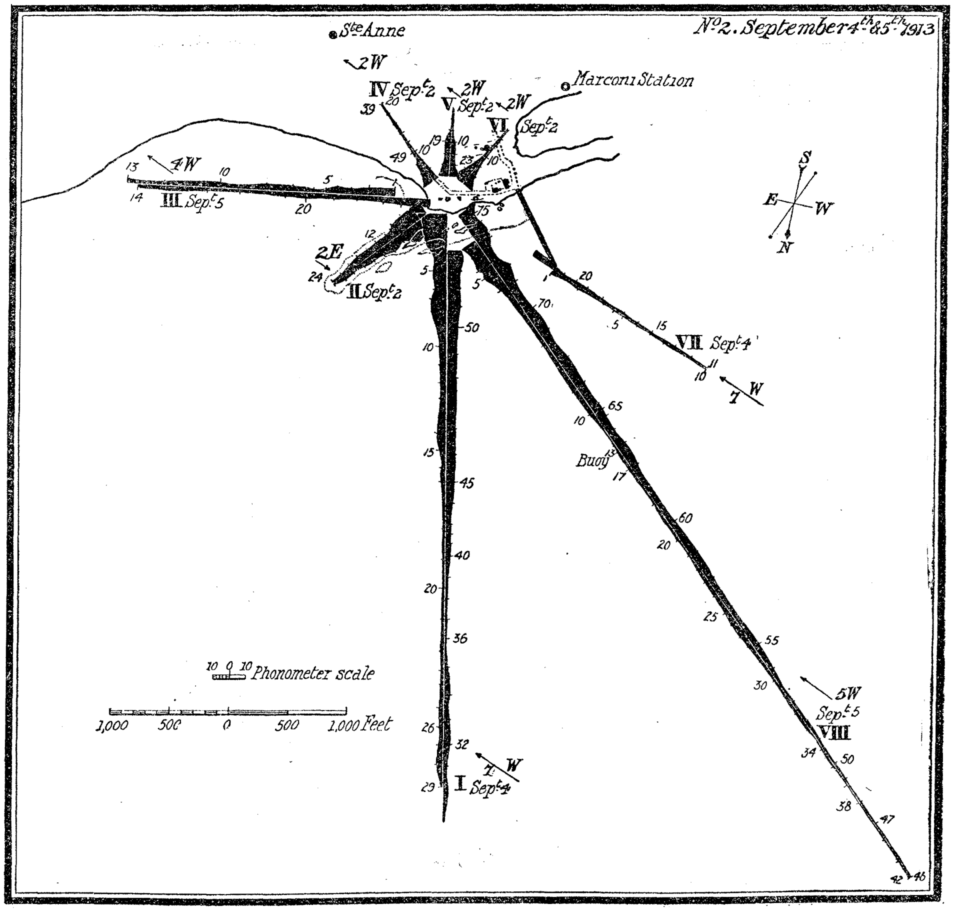
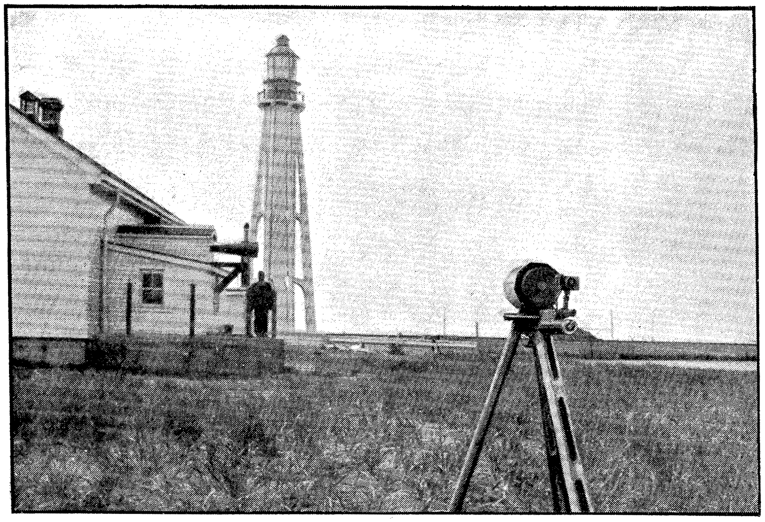


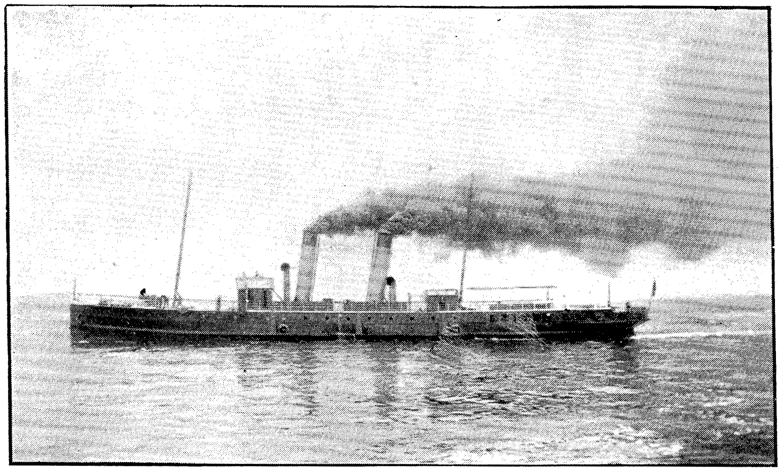
Chart 2. Short range acoustic survey, September 4 and 5, 1913.

Observations carried out from a ship's boat by means of the Webster phonometer. The position of the ship's boat at each signal (identified by means of the numbers on the chart) was obtained from sextant observations. The phonometer readings at each position are plotted along ordinates at right angles to the inward and outward courses. Wind directions and velocities (represented by arrows) are those registered at the meteorological station.

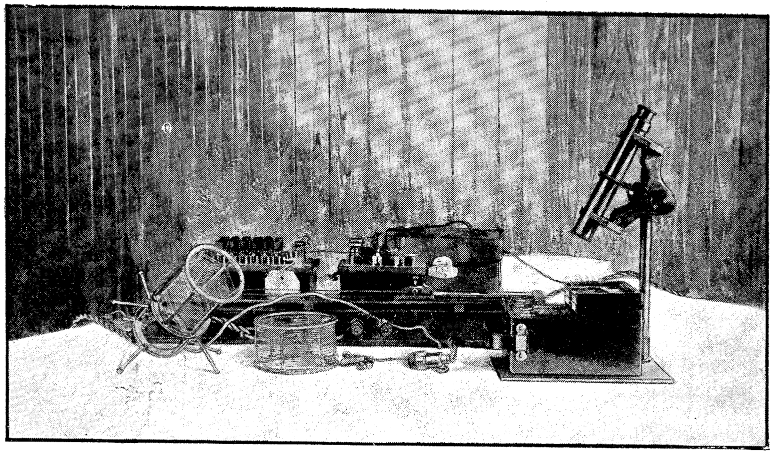


(i.) Webster phonometer mounted on a theodolite tripod. Building on the left is the fog-signal station, showing trumpet of diaphone. Father Point lighthouse in the background. The results obtained are shown graphically in Chart 1.

(ii.) Acoustic survey carried out from a ship's boat. The phonometer is shown mounted at the bow of the boat. The results obtained are shown graphically in Chart 2.



(iii.) C.G.S. "Lady Evelyn." From this ship were taken the phonometer observations for the long range acoustic surveys, the results of which are shown graphically in Charts 3 to 14.



(iv.) Apparatus for the thermal measurement of the acoustic output of diaphone. The skeleton construction of the iron-wire resistance thermometers is clearly shown.

of incipient "silent zones," the amplitude diminishing with distance and increasing again as the distance is further increased. The comparatively small amplitudes along line VII. are due in part to the wind blowing against the direction of sound propagation and in part to the obstructing effect of the wharf.

Nos. 3 *to* 14. *Long Range Acoustic Surveys.* (*Tables* 3 *to* 14, *Charts* 3 *to* 14?)

These observations were taken from the C.G.S. "Lady Evelyn" (Plate (iii).). The phonometer was set up on the main deck in such a position that an unobstructed view of the fog-signal station could be obtained. When the phonometer reading fell to 0·1 mm. the signal was still sufficiently loud for practical purposes. Signals which could still be heard, although incapable of affecting the phonometer, are entered in the tables as 0·0. In the remarks, the intensity of the signal as estimated by ear is entered according to the following scale—*distinct* (between 0·0 and 0·05 on the phonometer), *audible*, *just audible*, *barely audible*, *inaudible*. When a signal was missed or not heard owing to disturbing ship noises *a*— is entered in the table. On landing at Father Point wharf after a series of observations, a number of phonometer readings were taken at this position (W, Chart 1), and a note made of the duration of the echoes. A number of readings were also taken at a control station behind the fog-signal station (S, Chart 1), and observations were made of the air pressure operating the diaphone. It would have been desirable to have had a third observer available to regulate the compressors and keep the pressure constant; it was fortunate, as pointed out in Appendix I., that the pitch of the diaphone varies over a very small range for considerable variations of operating pressure. Also, as may be seen from an inspection of tests 1 and 3 of Appendix III., the acoustic output does not vary between very wide limits over a considerable range of pressures. Thus, although the pressures at the fog-signal station could not be maintained as constant as could be desired, it is concluded that the results of the acoustic survey as shown graphically on Charts 3 to 14 are comparable as regards conditions at the diaphone, and that the extraordinary variations of sound distribution observed from day to day are due for the most part to changes in atmospheric conditions. We proceed to direct attention to some of the outstanding features of the results obtained on these long-range surveys.

No. 3. *August* 26, 1913. *Table* 3 *and Chart* 3.

Wind (as recorded at Father Point meteorological station) very variable. Note effect on sound and the tendency to form regions of inaudibility. Close to the fog-signal station (observations 84 to 89) note the deadening effect of a wind blowing from the direction of the shore as compared with the influence of a steadier and more homogeneous wind blowing from the sea (observations 25 to 30). Unfortunately, no anemometer was available for shipboard use at the time these observations were taken.

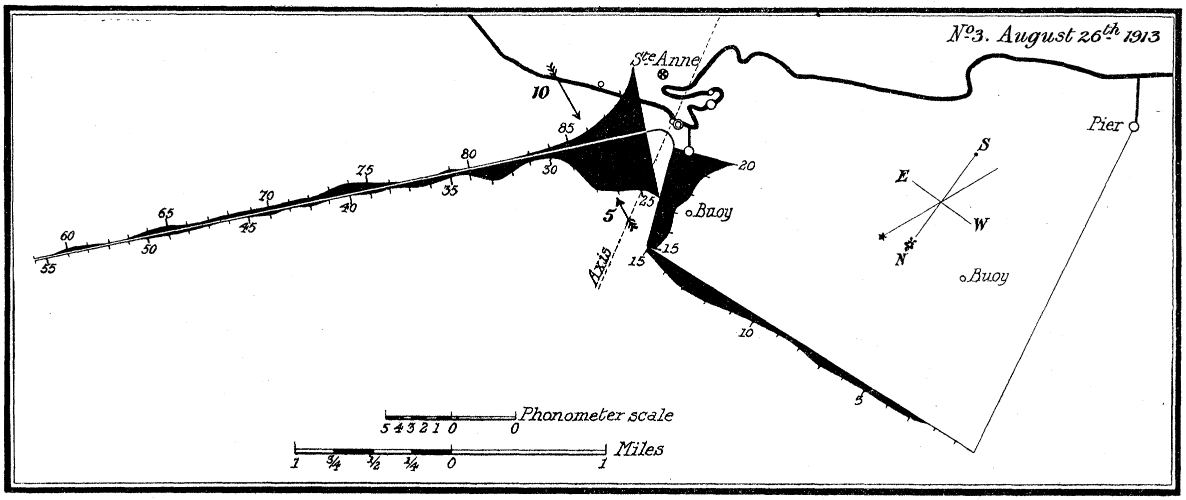


Chart 3. Acoustic survey, August 26, 1913.

No. 4. *August* 30, 1913. *Table* 4 *and Chart* 4.

Meteorological conditions unusually favourable to long-distance propagation. Note the fairly regular undulatory character of the gradient. In the writer's opinion this peculiarity affords evidence of some sort of regular structure in the wind explained by the existence of large scale eddies according to the theory proposed by TAYLOR and briefly discussed in Section 11. The question is discussed in greater detail in Section (iii.) of the present Appendix.

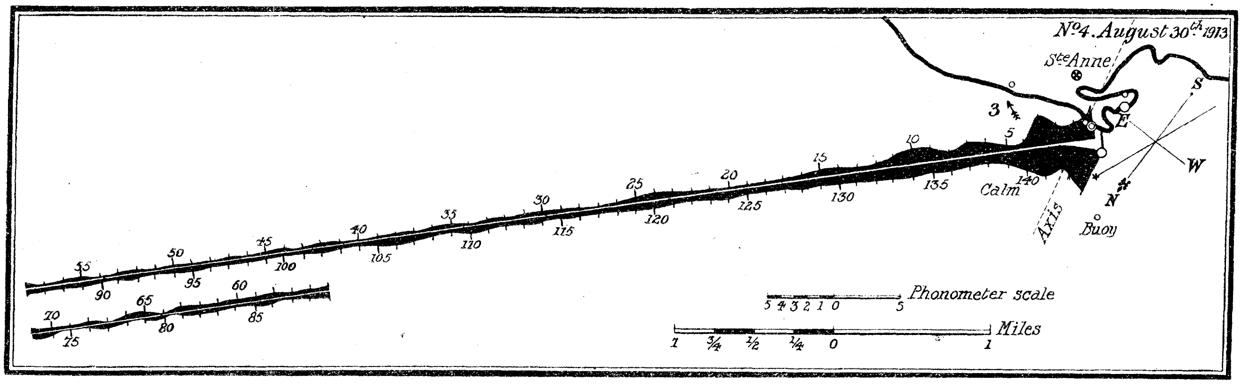


Chart 4. Acoustic survey, August 30, 1913.

No. 5. *September* 3, 1913. *Table* 4 *and Chart* 4.

Note the poor propagation against the wind (observations 1 to 6); the signal was first heard from the navigating bridge, about 10 feet above the observer at the phonometer and about 20 feet above sea level,

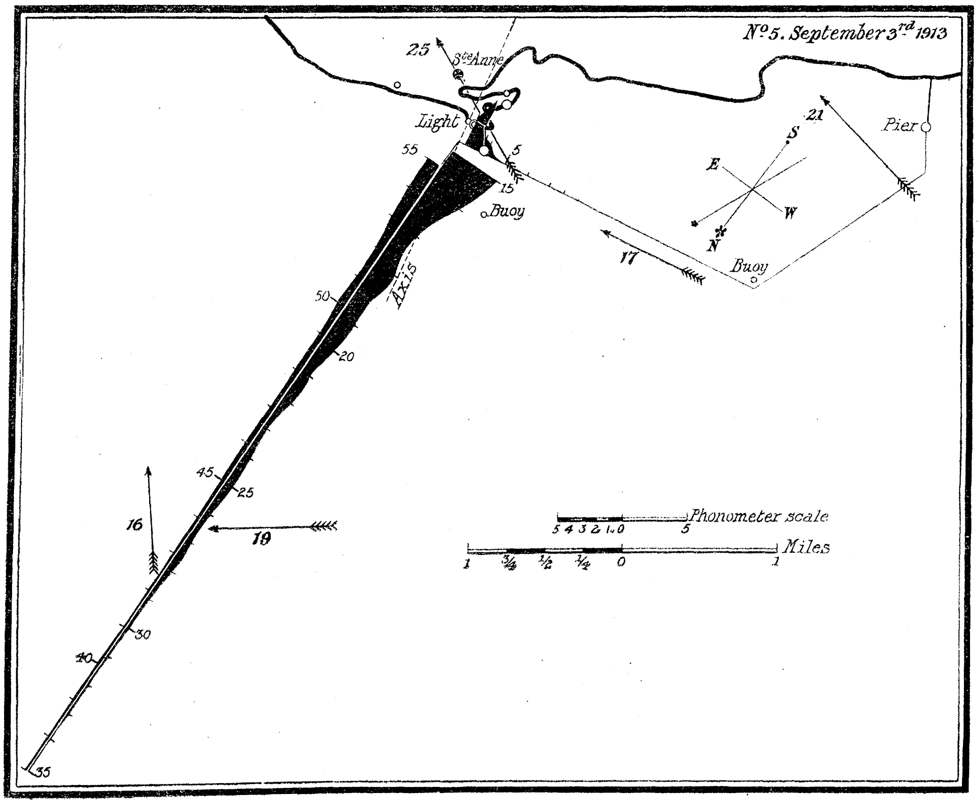


Chart 5. Acoustic survey, September 3, 1913.

thus bearing out the accepted theory of the refraction by an opposing wind of the sound over the observing ship. In spite of the comparatively high velocity of the wind, propagation at right angles to its direction remains fairly good (observations 15 to 35). On the inward course the wind veered to a direction opposite to that of sound propagation; the effect on the gradient is seen to be very marked.

No. 6. *September* 4, 1913. *Table* 6 *and Chart* 6.

The ship was kept to a circular course by navigating so as to keep the Father Point lighthouse directly abeam, and making corrections on the course by keeping the angle subtended by the top and bottom of the lighthouse constant. Note the diminution of intensity on entering the acoustic shadow of the Father Point wharf. The distribution of amplitude along the outer of the two circular courses is much greater than would be expected according to the inverse-square law of propagation, in spite of an opposing wing, indicating reinforcement by refraction from the upper layers of the atmosphere or by sound scattered from eddies. The subject is further discussed in Section (iii.) of the present Appendix.

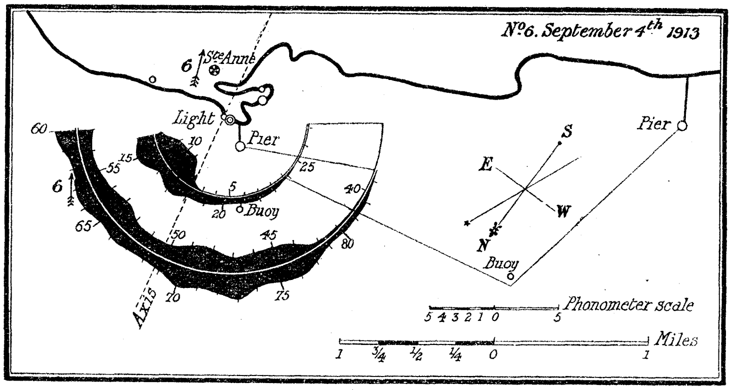


Chart 6. Acoustic survey, September 4, 1913.

No. 7. *September* 5, 1913. *Table* 7 *and Chart* 7.

A comparison with Chart 5 shows the deadening effect of an off-shore breeze. Besides containing large

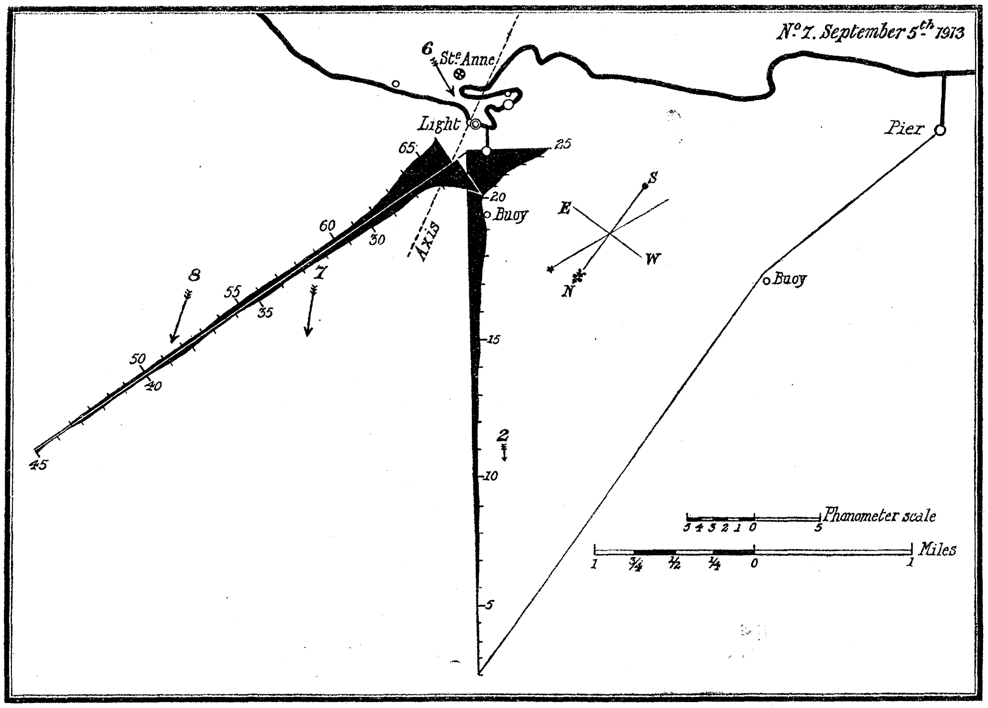


Chart 7. Acoustic survey, September 5, 1913.

temperature inequalities, the eddy-motion character of wind blowing over land is probably accentuated with a marked effect on the attenuation of sound.

No. 8. *September* 9, 1913. *Table* 8 *and Chart* 8.

The transmission of sound is seen to be extremely bad. This is probably due to the fact that the wind was blowing along the direction of the shore and thus contained marked temperature irregularities as well as more irregular eddy characteristics. On certain occasions with the wind in this quarter the alternations of warm and cool air may be distinctly felt.

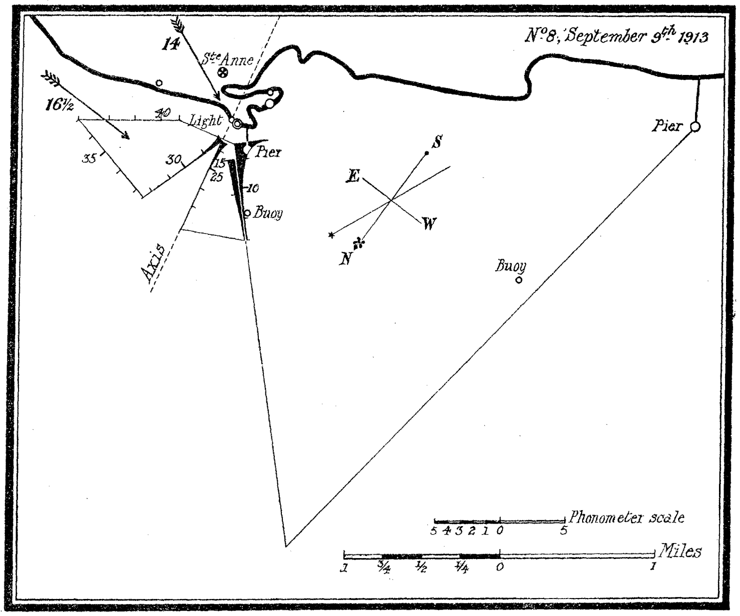


Chart 8. Acoustic survey, September 9, 1913.

No. 9. *September* 10, 1913. *Table* 9 *and Chart* 9.

A comparison with Chart 6 shows the unfavourable conditions for transmission of the signals set up by a wind blowing along the shore or from over the land, confirming conclusions already made.

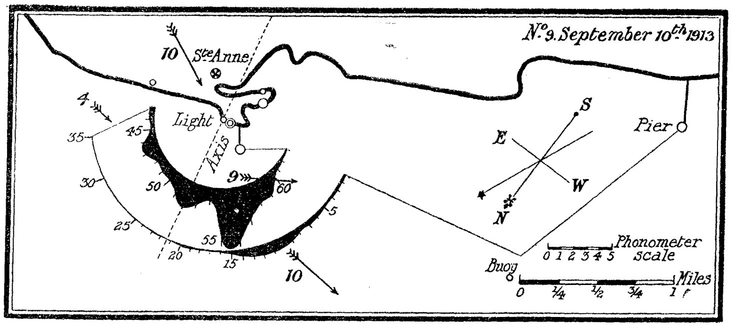


Chart 9. Acoustic survey, September 10, 1913.

No. 10. *September* 12, 1913. *Table* 10 *and Chart* 10.

Note the poor transmissions against the direction of the wind (observations 1 to 11). That the signal was first heard from the bridge confirms the refraction theory. The abnormally low phonometer reading at the control station is difficult to account for except that the wind was in a direction such that the influence of the lighthouse and adjoining buildings in creating eddies in the immediate neighbourhood of the diaphone trumpet was greatest. The possibility of eddies in the immediate neighbourhood of a fog-signal apparatus having an abnormally great effect in attenuating sound-waves of large amplitude should be made the subject of a special investigation.

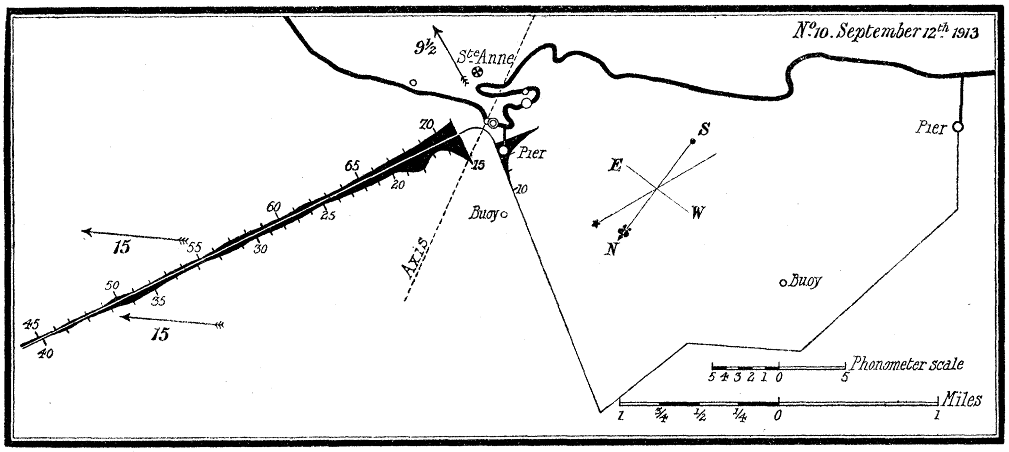


Chart 10. Acoustic survey, September 12, 1913.

No. 11. *September* 16, 1913. *Table* 11 *and Chart* 11.

Note the very poor transmission against the direction of the wind (observations 1 to 13) with relatively good conditions of propagation in a direction at right angles. In order to see to what an extent the distribution of sound was changed during a short interval of time, the same course inward and outward was repeated (observations 52 to 72). The curves show only a general resemblance. The effect of a wind in a direction opposite to that of the sound is very marked even at a distance as close as the end of Father Point wharf (1150 feet distant).

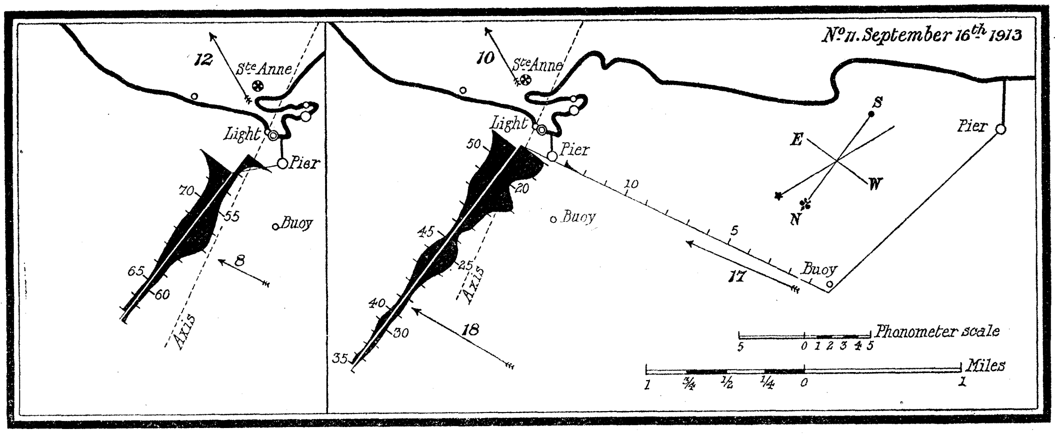


Chart 11. Acoustic survey, September 16, 1913.

No. 12. *September* 17, 1913. *Table* 12 *and Chart* 12.

Note the influence of the wind in strengthening the distribution of sound in the direction in which it is blowing.

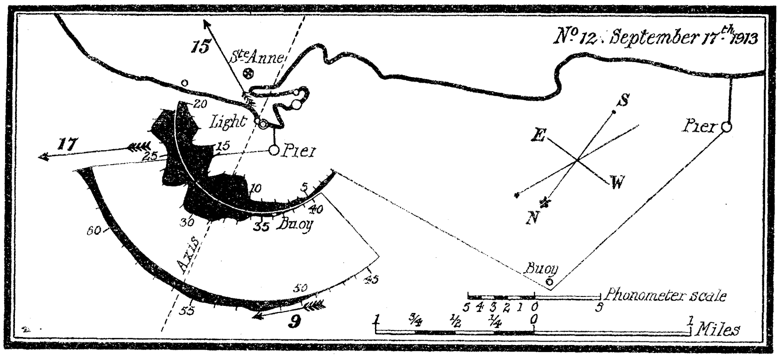


Chart 12. Acoustic survey, September 17, 1913.

No. 13. *September* 19, 1913. *Table* 13 *and Chart* 13.

Weather conditions unusually favourable to transmission of sound. The distribution over the circle of two miles radius is greater than can be accounted for by the inverse-square law of propagation. Note the remarkably uniform distribution over an arc of nearly 180 degrees.

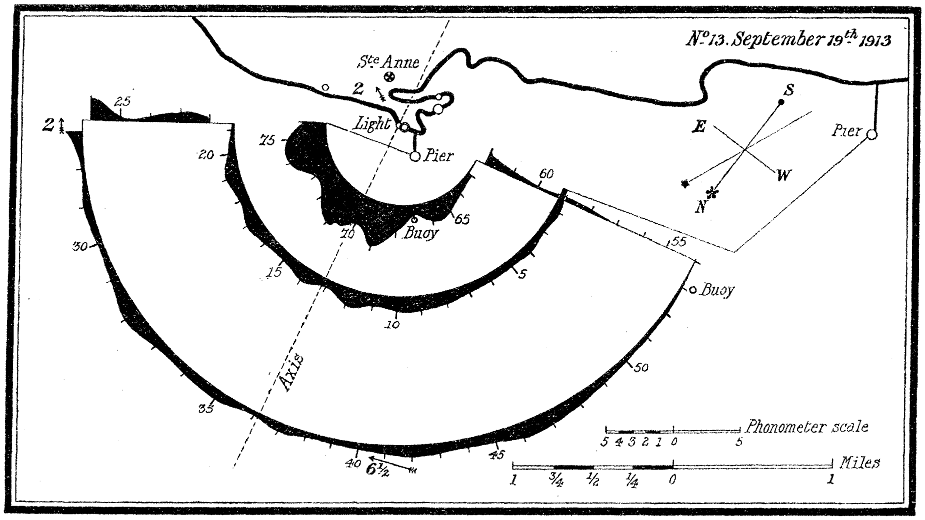


Chart 13. Acoustic survey, September 19, 1913.

No. 14. *September* 20, 1913. *Table* 14 *and Chart* 14.

Note the tendency to the formation of a "silent zone" (observations 30 to 33), and the enormously improved conditions of sound propagation during a temporary calm (observations 48 to 70).

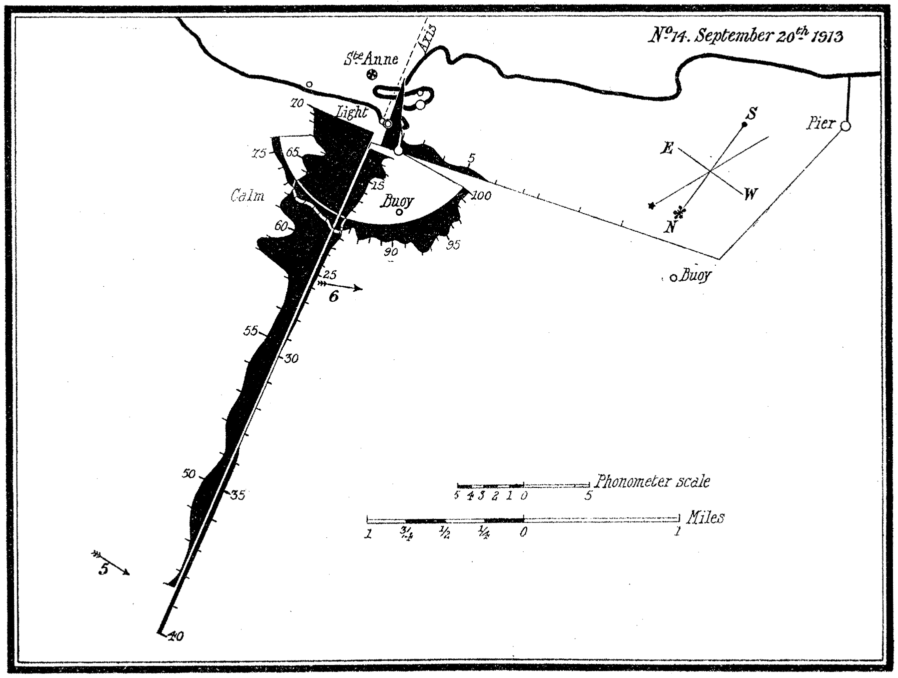


Chart 14. Acoustic survey, September 20, 1913.

(iii.) Discussion of Results of Acoustic Surveys.

(1) *Acoustic Gradients.*

It will be evident from an inspection of the charts we have just described that, even on the most favourable days, the atmosphere is so far from homogeneous that the propagation of sound according to the inverse-square law is an approximation of the roughest kind. It is of considerable interest, however, to compare the actual observed gradient of phonometer readings with the theoretical gradient calculated from the acoustic output of the diaphone, assuming ideal conditions of sound propagation. If $|\delta p|$ be the pressure amplitude at a distance r sufficiently great compared to a wave-length, the ratio of flow of energy across unit area of wave-front is very approximately given by

$$[dW/dt] = |\delta p|^2/(2a\rho_0). \qquad \text{(i.)}$$

Expressing the fact that the entire flow of energy across a hemisphere of radius r is equal to the acoustic output at the diaphone, we have

$$2\pi r^2 \times |\delta p|^2/(2a\rho_0) = \text{(acoustic output)}. \qquad \text{(ii.)}$$

If d is the phonometer reading in mm., we have from the known constant of the instrument

$$|\delta p| = 0 \cdot 708\, d. \qquad \text{(iii.)}$$

From a knowledge of the pressure of air operating the diaphone, we may obtain a rough estimate of the acoustic output from the results of the thermal tests 1 or 3 described in Appendix III.

In fig. (i.) are drawn on a large scale the gradients of phonometer readings obtained on August 30, 1913. According to test 1 of Appendix III., the acoustic output corresponding to an operating pressure of 19·9 lbs./sq. in. is 1·6 H.P. Expressing the distance R in feet, we obtain for the phonometer reading d the expression

$$d\,(\text{mm.}) \times [\text{R}\,(\text{feet})/1000] = 19\cdot 4 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(iii.)}$$

from which the theoretical gradient shown in fig. (i.) has been drawn. It will be noticed from the comparison of the two curves that a very large proportion of the atmospheric losses occur within a radius of $\frac{1}{2}$ mile. When once a sound-wave has traversed this distance, it is evident from fig. (i.) that on a calm day the subsequent losses are small. This conclusion is supported from an inspection of the acoustic gradients observed on other days.

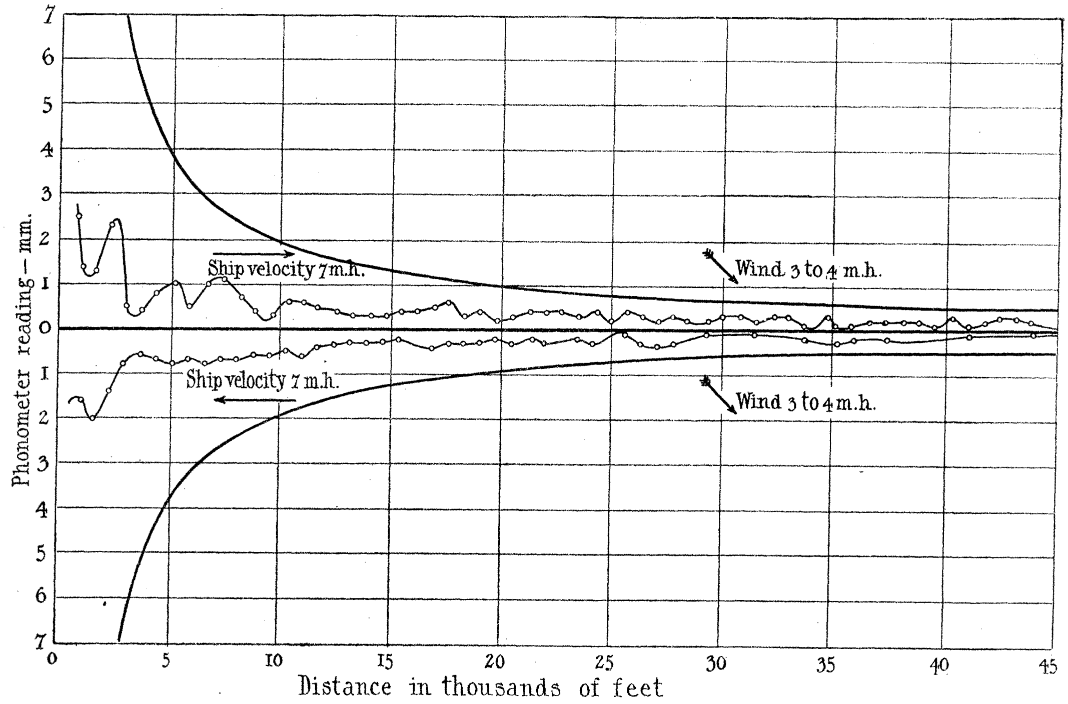


Fig. (i.). Acoustic gradient in the neighbourhood of Father Point diaphone, August 30, 1913.

The curious undulatory character of the gradient is well shown in fig. (i.), and lends support to Taylor's theory respecting the effect of atmospheric eddies on the attenuation of sound. The eddies may be supposed to be travelling with the average speed of the wind (3 to 4 statute miles per hour): the undulations are produced when the observing ship crosses successive eddies. The velocity of the ship was about 7 statute miles per hour. By a simple calculation the diameter of the eddies corresponding to a light breeze of 3·5 statute miles per hour, comes out to be about 700 feet or 230 metres, a result which may not be impossibly large.* Future observations in this connection should be carried out with a sound-generator (if possible of adjustable pitch) giving a continuous note, preferably from a ship anchored at a considerable distance from the land. Fluctuations of sound amplitude should then be measured by means of a phonometer situated at fixed distances directly to leeward and windward. In addition to obtaining wind-velocity, direction, and other meteorological data by self-registering instruments, means should be taken to observe the velocity gradient of the wind and its gustiness, from which the characteristics of the

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* According to Taylor ("Eddy Motion in the Atmosphere," 'Phil. Trans.,' A, 215, 1915, p. 22), the average diameter of an eddy in a wind of velocity 7 metres/sec. (21 statute miles per hour) is given as 40 metres. In light winds the diameter increases. As yet data on the subject are very incomplete.

eddy motion may be deduced.* The gradient of temperature and water-vapour content should also be observed if possible.

(2) *Distribution of Sound over Circular Courses.*

From the phonometer observations taken over circular courses it is possible to compare at different distances the energy flux across portions of zones of spheres near the surface of the sea, subtending a small angle $\delta\theta$ (in a vertical plane) at the fog-signal station and a horizontal angle ϕ on either side of the axis of the diaphone trumpet. If $[d\mathrm{W}/dt]$ is the flux of energy across unit area of a spherical wave-front at a distance r, the total flux of energy across the surface just referred to is given by

$$\iint r^2 [d\mathrm{W}/dt] \sin\theta \, d\theta \, d\phi \quad \text{(iv.)}$$

Making use of (i.) we have, since $\sin\theta$ is very nearly unity,

$$\text{energy flux} = \frac{r^2 \delta\theta}{2a\rho_0} \int_{-\phi}^{\phi} |\delta p|^2 d\phi. \quad \text{(v.)}$$

Since the phonometer readings were taken at approximately equal intervals over the circular courses, the integral in (v.) may be written $2\phi\,[|\delta p|^2]$, where $[|\delta p|^2] = (0{\cdot}708)^2 [d^2]$ is the mean square of the pressure amplitude between the angles $\pm\,\phi$. The value of $\delta\theta$ is chosen somewhat arbitrarily as the angle subtended by a vertical height of 40 feet at a distance of one nautical mile. Within the solid angle thus constituted is contained the sound which may be serviceable as a warning to ships. Inserting numerical values in (v.), we have, expressing the distance R in feet,

$$\text{energy flux} = 3{\cdot}47 \times 10^{-3} \,.\, (\mathrm{R}/1000)^2 \,.\, 2\phi \times [d^2] \text{ watts.} \quad \text{(vi.)}$$

It is of some interest to compare the energy flux thus observed with the theoretical value calculated from the acoustic output of the diaphone, assuming that the sound is equally distributed in all directions throughout a hemisphere and that conditions of propagation are ideal. In these circumstances we have

$$\text{theoretical energy flux} = \sin\theta \; \delta\theta \; (2\phi/2\pi) \times (\text{acoustic output}),$$

or for purposes of numerical calculation, expressing the acoustic output in H.P., we have, inserting the value $\delta\theta = 40/6080$,

$$\text{theoretical energy flux in watts} = (2\phi/2\pi) \times 4{\cdot}9 \times (\text{acoustic output in H.P.}) \quad \text{(vii.)}$$

The acoustic output corresponding to the air pressure operating the diaphone is obtained from the results of the thermal tests tabulated in Appendix III. Before September 13, the acoustic outputs are determined from test 1 and after September 16 from test 3, as the valves admitting air to the diaphone were readjusted in the interval. The results of the acoustic surveys taken over circular courses are tabulated below.

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* The linear hot-wire anemometer, adapted to take continuous records, would appear to be suitable for this purpose (King, L. V., 'Phil. Mag.,' vol. 29, April, 1915, pp. 556-577).

TABLE I.

Date and remarks.	R.	Observation numbers.	$[d^2]$	Energy flux in solid angle.	Theoretical energy flux.
	(feet)		(mm.)^2	watts.	watts.
No. 6. September 4, 1913 .	3040	3–12	1·205	0·07	
		14–22	0·74	0·04	
$\phi = 50^\circ$ $\delta\theta = 40/6080$.	6080	45–56	1·73	0·39	1·63
		62–76	1·24	0·28	
Acoustic output = 1·2 H.P. .					
No. 9. September 10, 1913 .	2600	45–60	3·72	0·18	
$\phi = 60^\circ$ $\delta\theta = 40/6080$.	5100	8–35	0·10	0·02	2·61
Acoustic output = 1·6 H.P. .					
No. 12. September 17, 1913 .	3500	7–17	3·20	0·24	
		25–38	1·27	0·10	
$\phi = 50^\circ$ $\delta\theta = 40/6080$.	7000	48–63	0·43	0·13	2·31
Acoustic output = 1·7 H.P. .					
No. 13. September 19, 1913 .	3040	65–75	4·98	0·33	
$\phi = 60^\circ$ $\delta\theta = 40/6080$.	6080	6–20	0·66	0·18	2·77
Acoustic output = 1·7 H.P. .	12160	28–48	0·46	0·49	
No. 14. September 20, 1913 .	4000	74–96	1·44	0·17	
$\phi = 60^\circ$ $\delta\theta = 40/6080$.	—	—	—	—	2·77
Acoustic output = 1·7 H.P. .					

The above table shows in several cases that the energy flux in the same solid angle is in some cases greater at 1 mile than at ½ mile (No. 6), and in one instance (No. 13) considerably greater at 2 miles than at either 1 mile or ½ mile. According to the inverse-square law of sound propagation, these estimates should be the same. We are obliged to conclude that contributions to the energy flux at these greater distances are made by refraction or by reflection from the upper regions of the atmosphere, and to some extent, possibly, by the sound scattered by atmospheric eddies reaching the observer from all directions.

A comparison of the last two columns of Table I. shows that within the half-mile radius a large proportion of the energy is lost, confirming the conclusion already made as to the comparatively small atmospheric losses beyond this distance.

(iv.) NOTE ON ACOUSTIC SHADOWS.

During the course of the acoustic surveys several opportunities offered of observing the effects of obstacles in giving rise to acoustic shadows.

On September 2, 1913 (see Chart 1), phonometer observations were taken on both sides of the wharf along line VII. The wharf was 15 feet above the level of the beach and was 37 feet broad, consisting of timber cribwork filled with heavy stones.

The following readings were taken:—

(1) 5 feet above beach and about 2 feet from nearer vertical wall . . . . 1·1
(2) On wharf 15 feet higher on edge nearest to signal . . . . 2·4
(3) On wharf at most distant edge. . . . . 1·2
(4) In acoustic shadow 5 feet above beach and 2 feet from further vertical wall . . 0·2
(5) 10 feet from foot of wharf in acoustic shadow . . . . 0·3
(6) 20 feet from foot of wharf in acoustic shadow. . . . . 1·0

That the reading at position (2) at the higher level is considerably greater than that at position (1) nearer the ground may be attributed to the attenuation of the sound by the rough ground intervening between the wharf and the fog-signal.

On September 19, a few observations were taken in the neighbourhood of the lighthouse (L, Chart 1), built of concrete in the form of an octagonal cylinder about 15 feet in diameter supported by eight flying buttresses (Plate (i)). Phonometer reading on nearer side of lighthouse, 9·0, on opposite side in acoustic shadow, 4·7.

In taking observations from the C.G.S. "Lady Evelyn" it was noticed when manœuvring close to the fog-signal that whenever the fog-signal could not be viewed directly from the phonometer, owing to the interposition of one of the deck structures in the line of sight, the readings were sensibly diminished, indicating the existence of noticeable shadows.

In the case of obstacles of smaller dimensions (*e.g.*, empty sheet-iron gasoline drums, about 2 feet in diameter) no appreciable acoustic shadows could be detected.

TABLE 1.—SHORT RANGE ACOUSTIC SURVEY, September 2, 1913.

Father Point Meteorological Observations.

Barometer, 30·22. Air temperature: dry bulb, 56° F.; wet bulb, 53° F.

Wind, very light breeze during forenoon. Velocity: 10–11 a.m., 2 miles per hour from E.; 11–12 a.m., 2 miles per hour from E.; 12–1 p.m., 9 miles per hour from E.; 1–2 p.m., 5 miles per hour from E.; 2–3 p.m., 2 miles per hour from W.; 3–4 p.m., 2 miles per hour from W.; 4–5 p.m., 4 miles per hour from W.

Weather during forenoon, clear. Few clouds visible. Sky 10 per cent. overclouded. Sky becomes overcast and wind veers about 2.30 p.m.

PHONOMETER READINGS.

Note.—Readings taken at positions 50 feet apart and are entered in chronological order. Position 1 is in each case 50 feet from the resonator of the diaphone. Unless otherwise indicated by a suffix, the entries are the mean of the two readings for each of the 3-second blasts. All readings, other than those enclosed in brackets ( ), were taken with resonator in position 8.

Line II.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	—	11	$7\cdot0_1$	21	2·1	31	3·1	41	$10\cdot1_3$
2	—	12	$4\cdot7_1$	22	1·4	32	$2\cdot8_6$	42	$11\cdot3_3$
3	$10\cdot5_1$	13	$4\cdot8_1$	23	$1\cdot5_1$	33	$3\cdot4_3$	43	$8\cdot1_6$
4	$9\cdot7_1$	14	$4\cdot9_1$	24	1·1	34	$5\cdot6_1$	44	9·2
5	$10\cdot0_1$	15	$4\cdot1_1$	25	1·1	35	$4\cdot5_1$	45	9·7
6	$9\cdot4_1$	16	4·6	26	$1\cdot2_4$	36	$4\cdot4_1$	46	$7\cdot9_5$
7	$9\cdot5_1$	17	4·9	27	1·5	37	$6\cdot2_1$	47	$13\cdot8_3$
8	$9\cdot3_1$	18	$4\cdot0_3$	28	2·9	38	$7\cdot2_1$	48	($>$46)
9	$8\cdot2_1$	19	3·7	29	1·9	39	$9\cdot2_6$		
10	$8\cdot0_1$	20	3·4	30	1·9	40	11·0		

Remarks.

Readings plotted on Charts 1 and 2. Wind, 2 miles per hour from E. Observations at control station, 10.27 a.m.: mean of three phonometer readings, 7·7.

1–2. Readings off scale. 24. Most distant station on Line II., 1200 feet; echo audible for 45 seconds. 39. Resonator at positions 6 and 8; readings, $4 \cdot 2_4$ and $11 \cdot 0_2$. 40. Resonator at positions 6 and 8; readings, $3 \cdot 1_8$ and $9 \cdot 2_6$. 47. Resonator at positions 0, 2, 4, 6, and 8; readings, 8·4, 8·2, 8·4, 12·5, and 13·8. 48. Resonator at position 0, reading >28; entry calculated for position 8 from observation 47 above.

Line I.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	—	4	$15 \cdot 0_3$	7	6·7	9	13·2	11	17·0
2	—	5	9·9	8	10·6	10	15·0	12	(33·0)
3	—	6	6·7						

Remarks.

Readings plotted on Chart 1. Wind, 2 miles per hour from W.

1–3. Resonator at position 0; readings off the scale. 4. Resonator at positions 0, 6, and 8; readings, 5·0, 9·1, and 15·0. 6. Most distant station of Line I., 300 feet. 11. Resonator at positions 4 and 8; readings 10·0 and 17·0. 12. Resonator at position 4; reading, 19·5; entry for position 8 calculated from observation 11 above.

Line VIII.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	(36)	4	7·0	7	6·4	10	6·2	13	4·3
2	(16·0)	5	4·6	8	2·2	11	7·6	14	7·9
3	$9 \cdot 3_4$	6	7·5	9	2·7	12	6·8	15	12·4
								16	(45)

Remarks.

Readings plotted on Chart 1. Wind, 2 miles per hour from E.

1. Resonator at position 4; reading, 21; entry calculated for position 8 from observation 11 of Line I. 2. Resonator at position 4; reading, 9·4; entry calculated for position 8 from observation 11 of Line I. 8. Most distant station, 400 feet. 16. Resonator at position 0; reading, 15; entry calculated for position 8 from observation 4 of Line I. Reading at end of Father Point wharf, distant 1150 feet, $2 \cdot 6_7$.

Line VII.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	(36)	6	2·5	11	2·0	16	1·75	21	3·4
2	5·4	7	3·0	12	1·6	17	2·2	22	3·9
3	6·8	8	2·4	13	1·1	18	3·2	23	2·2
4	3·8	9	2·5	14	1·0	19	2·0	24	3·0
5	2·6	10	2·8	15	1·05	20	1·9	25	10·5
								26	(37)

Remarks.

Readings plotted on Charts 1 and 2. Wind, 2 miles per hour from E. Sky becomes lightly clouded over.

1. Resonator at position 0; reading, 12·0; entry calculated for position 8 from observation 4 of Line I. 13. Most distant station, 650 feet. 26. Resonator at position 0; reading, 12·7; entry calculated for position 8 from observation 4 of Line I.

Line III.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	(22·5)	3	6·2	5	5·2	7	6·5	9	7 6
2	7·8	4	—	6	5·2	8	7·2	10	(19·2)

Remarks.

Readings plotted on Chart 1. Wind, 2 miles per hour from E. Time, 12·02 p.m.

1. Resonator at position 0; reading, 15·0; entry for position 8 calculated from observation 2 below. 2. Resonator at positions 0 and 8; readings, 5·2 and 7·8. 5. Most distant station, 250 feet. 10. Resonator at position 0; reading, 12·8; entry calculated for position 8 from observation 2 above. Observations at control station, 12.25 p.m.; mean of three phonometer readings, 8·0.

Line IV.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	(16·1)	13	0·7	25	0·25	37	0·2	49	1·5
2	$5{\cdot}8_3$	14	0·4	26	0·2	38	0·2	50	2·8
3	$7{\cdot}8_3$	15	0·6	27	0·2	39	—	51	2·75
4	4·2	16	0·5	28	0·1	40	0·3	52	3·2
5	$3{\cdot}4_4$	17	—	29	0·2	41	—	53	3·7
6	$2{\cdot}6_3$	18	—	30	—	42	0·4	54	—
7	2·2	19	0·25	31	—	43	0·7	55	7·3
8	1·7	20	0·25	32	—	44	0·7	56	7·8
9	1·0	21	0·2	33	—	45	0·9	57	5·0
10	0·8	22	0·25	34	0·25	46	0·7	58	7·1
11	0·7	23	0·2	35	—	47	1·1		
12	0·6	24	0·3	36	—	48	1·8		

Remarks.

Readings plotted on Chart 1. Wind, 2 miles per hour from W., and variable.

1. Resonator at position 0; reading, 5·0; entry for position 8 calculated from observation 2 below. 2. Resonator at positions 0 and 8; readings, $1{\cdot}8_4$ and $5{\cdot}8_3$. 29. Most distant station, 1450 feet. 45. Wind changes direction. 48. Wind at right angles to direction of sound. 50. Wind along direction of sound. 55. Wind drops to calm.

Line VI.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	5·6	7	3·1	13	0·4	19	0·75	25	4·7
2	$5{\cdot}4_6$	8	1·9	14	0·7	20	0·65	26	6·8
3	3·4	9	0·6	15	0·4	21	0·9	27	7·8
4	7·0	10	0·9	16	0·3	22	1·2	28	4·9
5	5·6	11	0·5	17	0·7	23	2·2	29	$3{\cdot}3_5$
6	3·3	12	1·0	18	0·6	24	3·9	30	$8{\cdot}3_3$

Remarks.

Readings plotted on Charts 1 and 2. Wind, 2 miles per hour from W., and very variable.

15. Most distant station, 750 feet. Wind from W. Thunder clouds moving up from N.W. 20. Time 2.14 p.m. Slight shower of rain commences. 28. Wind dies away completely.

Line V.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	6 ·4$_3$	7	3 ·6	13	1 ·0	19	3 ·6	25	6 ·8
2	6 ·4$_5$	8	3 ·0	14	0 ·7	20	3 ·4	26	9 ·1
3	7 ·7	9	2 ·3	15	0 ·85	21	3 ·65	27	3 ·8
4	7 ·4	10	2 ·7	16	0 ·65	22	3 ·35	28	7 ·5
5	5 ·2	11	1 ·8	17	0 ·85	23	4 ·3		
6	3 ·4	12	0 ·6	18	1 ·45	24	6 ·2		

Remarks.

Readings plotted on Charts 1 and 2. Wind, 2 miles per hour from W.

14. Most distant station, about 700 feet. Time, 3.43 p.m. Reading at end of Father Point wharf, 4 ·2.

TABLE 2.—SHORT RANGE ACOUSTIC SURVEY, September 4 and 5, 1913.

Father Point Meteorological Observations, September 4.

Barometer, 30 ·21. Air temperature: dry bulb, 47° F.; wet bulb, 43° F.

Wind: steady; 3–4 p.m., velocity 7 miles per hour from W.; 4–5 p.m., velocity 7 miles per hour from W.

Weather, clear. Sky unclouded during observations.

PHONOMETER READINGS.

Line VII. September 4.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	2 ·5	6	0 ·6	11	0 ·2	16	0 ·3	21	1 ·1
2	1 ·4	7	0 ·4	12	0 ·4	17	0 ·6	22	3 ·5
3	1 ·0	8	0 ·4	13	0 ·3	18	0 ·7	23	4 ·2
4	0 ·8	9	0 ·2	14	0 ·4	19	1 ·8	24	5 ·0
5	0 ·8	10	0 ·2	15	0 ·3	20	1 ·0		

Remarks.

Readings plotted on Chart 2. Wind, 7 miles per hour from W. Sea smooth.

1. Time, 3 ·45 p.m. Boat close to end of Father Point wharf. 10. Turned back along same line. 22. Boat close to end of Father Point wharf.

Line I. September 4.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	>20	12	3 ·5	23	1 ·5	34	3 ·5	45	5 ·5
2	17 ·0	13	3 ·8	24	1 ·3	35	2 ·3	46	5 ·5
3	15 ·0	14	5 ·3	25	2 ·3	36	1 ·5	47	6 ·5
4	10 ·0	15	4 ·3	26	1 ·8	37	1 ·5	48	5 ·0
5	9 ·0	16	2 ·8	27	2 ·3	38	1 ·6	49	6 ·0
6	8 ·0	17	3 ·0	28	3 ·3	39	2 ·0	50	7 ·0
7	10 ·0	18	1 ·5	29	1 ·0	40	3 ·5	51	7 ·5
8	8 ·2	19	1 ·5	30	3 ·1	41	3 ·0	52	7 ·3
9	5 ·0	20	1 ·5	31	2 ·0	42	3 ·0	53	8 ·5
10	5 ·0	21	1 ·5	32	3 ·5	43	3 ·8	54	9 ·3
11	5 ·0	22	1 ·4	33	3 ·0	44	4 ·3	55	8 ·0

Remarks.

Readings plotted on Chart 2. Wind, 7 miles per hour from W. Sea smooth.

1. Time, 4.18 p.m. Reading off scale. 29. Turned back along same line.

Control station.—Phonometer reading, 5 ·0.

Mean air-pressure operating diaphone, 19 ·9 lbs. per sq. inch above atmospheric.

Father Point Meteorological Observations, September 5.

Barometer, 29·97. Air temperature: dry bulb, 47° F.; wet bulb, 44° F.

Wind: steady; 3–4 p.m., velocity 5 miles per hour from W.; 4–5 p.m., velocity 4 miles per hour from W.; 5–6 p.m., velocity 4 miles per hour from W. Weather clear. Sky unclouded during observations.

Phonometer Readings.

Line VIII. September 5.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	(10·5)	17	1·7	33	1·7	49	0·6	65	5·8
2	(6·0)	18	1·1	34	1·0	50	0·9	66	5·9
3	8·4	19	1·6	35	1·1	51	1·0	67	6·5
4	6·0	20	1·6	36	1·2	52	1·4	68	6·3
5	7·8	21	1·4	37	0·8	53	1·6	69	6·0
6	4·7	22	1·4	38	0·8	54	2·4	70	6·0
7	3·0	23	2·6	39	0·4	55	2·6	71	6·8
8	2·7	24	2·5	40	0·2	56	3·3	72	9·3
9	3·5	25	3·0	41	0·3	57	3·3	73	9·0
10	2·9	26	2·7	42	0·7	58	3·6	74	9·6
11	1·6	27	3·3	43	0·4	59	4·3	75	10·0
12	0·9	28	2·3	44	0·3	60	3·6	76	12·5
13	1·3	29	2·3	45	0·4	61	4·4		
14	1·4	30	1·7	46	0·5	62	5·2		
15	1·1	31	1·7	47	0·3	63	4·8		
16	1·1	32	1·9	48	0·3	64	5·8		

Remarks.

Readings plotted on Chart 2. Wind, 5 miles per hour from W. Sea smooth.

1. Time, 4.15 p.m. 1–2. Resonator at position 0; readings, 3·5 and 2·0; entries calculated for position 8 from observation 4. Line 1 of Table 1. 44. Time, 5.10 p.m., turned back along same line.

Line III. September 5.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	5·5	7	3·4	13	2·5	19	2·3	25	4·3
2	5·0	8	3·5	14	2·3	20	3·0	26	4·6
3	4·6	9	2·2	15	2·8	21	2·6		
4	4·5	10	3·1	16	1·9	22	2·7		
5	2·6	11	2·3	17	1·9	23	3·0		
6	2·2	12	2·4	18	2·3	24	3·6		

Remarks.

Readings plotted on Chart 2. Wind, 4 miles per hour from W. Sea smooth.

13. Turned back along same line. 26. Boat grounded on beach.

Control station.—Mean of two readings, 33.

Mean air-pressure operating diaphone at conclusion of observations, 18·3 lbs. per sq. inch above atmospheric.

TABLE 3.—LONG RANGE ACOUSTIC SURVEY, August 26, 1913.

Father Point Meteorological Observations.

Barometer, 30·00. Air temperature: dry bulb, 50° F.; wet bulb, 46° F.

Wind: variable in direction during observations. Velocity: 8–9 a.m. (Position Nos. 0–10), 5 miles per hour from W.; 9–10 a.m. (Position Nos. 10–69), velocity 7 miles per hour to commence with: wind veers by S. and N. to wind from E.; 10–11 a.m. (Position Nos. 69–89), velocity 10 miles per hour from E.

Weather: cloudy; clouds almost stationary. Sky 80 per cent. overcast.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	—	19	2·9	37	0·3	55	—	73	0·6
2	—	20	4·8	38	0·1	56	—	74	0·7
3	0·3	21	3·2	39	0·1	57	—	75	0·5
4	0·3	22	3·4	40	0·0	58	—	76	0·3
5	0·4	23	5·0	41	0·0	59	0·0	77	0·0
6	0·5	24	4·2	42	0·2	60	0·3	78	0·0
7	0·7	25	5·2	43	0·0	61	0·3	79	0·2
8	0·4	26	4·0	44	0·3	62	0·1	80	0·0
9	0·3	27	3·8	45	0·0	63	0·1	81	0·0
10	0·5	28	3·5	46	0·0	64	0·3	82	0·0
11	0·7	29	1·0	47	0·2	65	0·3	83	0·2
12	1·2	30	0·3	48	0·2	66	0·2	84	0·3
13	1·2	31	0·2	49	0·2	67	0·2	85	0·45
14	0·6	32	0·7	50	0·1	68	0·3	86	0·9
15	0·6	33	1·1	51	0·0	69	0·2	87	1·8
16	1·5	34	0·3	52	0 0	70	0·3	88	2·6
17	1·4	35	0·2	53	—	71	0·4	89	5·0
18	2·3	36	0·4	54	—	72	0·3		

Remarks.

8. 44 a.m. Left Rimouski wharf.

1. Signal first heard. 11. Air temperature, 50° F. 19. Ship just off Father Point wharf. 25. Time, 9.15 a.m. Course set outwards from fog-signal station. 41. Signal audible. 53–56. Escape steam blowing off: signals not heard. 57. Time, 9. 47 a.m. Ship turned on course back to Father Point. 63. Air temperature, 51° F. 77. Signal just audible. Air temperature, 52° F. 89. Time, 10. 10 a.m. Ship opposite Father Point wharf.

TABLE 4.—LONG RANGE ACOUSTIC SURVEY, August 30, 1913.

Father Point Meteorological Observations.

Barometer, 29·65. Air temperature : dry bulb, 48° F. ; wet bulb, 47° F.

Wind: very light; velocity: 9–10 a.m., 3 miles per hour; 10–11 a.m., calm. Direction from W. Weather hazy. Clouds moving very slowly from W. Sky completely clouded over.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
0	2·5	30	0·4	60	0·2	90	—	120	0·4
1	1·4	31	0·4	61	0·2	91	0·1	121	—
2	1·3	32	0·3	62	0·2	92	0·2	122	0·2
3	2·3	33	0·4	63	0·3	93	0·1	123	0·3
4	0·5	34	0·2	64	0·0	94	0·2	124	0·3
5	0·4	35	0·4	65	0·3	95	0·3	125	0·3
6	0·8	36	0·3	66	0·3	96	0·1	126	0·35
7	1·0	37	0·2	67	0·0	97	0·2	127	0·4
8	0·5	38	0·3	68	0·1	98	0·1	128	0·6
9	1·0	39	0·2	69	0·1	99	—	129	0·5
10	1·1	40	—	70	0·15	100	0·1	130	0·6
11	0·7	41	0·3	71	0·2	101	0·1	131	0·6
12	0·4	42	0·3	72	0·2	102	0·2	132	0·7
13	0·3	43	0·2	73	0·2	103	0·1	133	0·7
14	0·6	44	0·3	74	0·1	104	0·1	134	0·8
15	0·6	45	0·3	75	0·0	105	0·3	135	0·7
16	0·5	46	0·1	76	0·0	106	0·35	136	0·8
17	0·4	47	0·3	77	0·1	107	0·3	137	0·7
18	0·3	48	0·1	78	0·0	108	0·1	138	0·6
19	0·3	49	0·1	79	0·1	109	0·1	139	0·8
20	0·3	50	0·2	80	0·0	110	0·3	140	1·4
21	0·4	51	0·2	81	0·1	111	0·2	141	2·0
22	0·4	52	0·2	82	0·2	112	0·2	142	1·6
23	0·5	53	0·2	83	0·05	113	0·3	143	2·8
24	0·6	54	0·1	84	0·1	114	0·2	144	3·0
25	0·3	55	0·3	85	0·1	115	0·3	145	4·5
26	0·4	56	0·1	86	0·05	116	0·2		
27	0·2	57	0·2	87	0·1	117	0·3		
28	0·3	58	0·3	88	0·1	118	0·3		
29	0·4	59	0·3	89	0·2	119	0·3		

Remarks.

8.28 a.m. Left Rimouski wharf. Light fog over sea. Sea unruffled. Signal just audible. 8.29–8.59 a.m. Course to Father Point wharf. Signal heard over entire course. 8.56 a.m. Ship abeam Father Point wharf. Phonometer reading, 0·9. Echo audible 20 seconds.

0. Time, 9.01 a.m. Started course from fog-signal. 8. Air temperature, 50° F. Echo audible 10 seconds. 9. Sky heavily overcast; light rain. 22. Rain stops. 33. Sky overhead clears, and sun commences to shine. 37. Sun shining brightly; smoke from ship hangs low. 40. Signal not heard. 55. Breeze freshening. 64. Signal barely audible. 67–69. Signals just audible. 71–73. Time, 10.20 a.m. Ship turns at end of course. Distance from fog-signal, 8·64 nautical miles. 75–76. Signals barely audible. Air temperature, 52° F. 77. Signal just audible, but distinct. 80–81. Signal barely audible. Termination of signal distinct. 99. Signal not heard. 102. Noticeable increase in audibility. Air temperature, 50° F. 105–107. Marked increase in audibility. Sky overcast. 133. Echo of signal marked. 144. Echo audible 15 seconds.

Control Observations.

End of Father Point wharf.—Mean of four phonometer readings, 4·5. Echoes heard for 23, 19, and 21 seconds. Maximum of echo (5 to 6 seconds after termination of second blast) gave phonometer reading about 0·2. Interval between 3-second blasts not detectable in echo.

Control station.—Mean of nine phonometer readings, 7·0.

Mean air pressure operating diaphone, 19·9 lbs./sq. in. above atmospheric.

TABLE 5.—LONG RANGE ACOUSTIC SURVEY, September 3, 1913.

Father Point Meteorological Observations.

Barometer, 30·19. Air temperature: dry bulb, 57° F.; wet bulb, 55° F.

Wind: steady. Velocity: 10–11 a.m., 25 miles per hour; 11–12 a.m., 26 miles per hour. Direction: from W. Clouds strato-cumulus moving from W. Sky 90 per cent. overcast.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	0·0	13	1·55	25	0·5	37	0·1	49	0·45
2	0·0	14	3·5	26	0·3	38	0·0	50	0·6
3	0·0	15	4·0	27	0·4	39	0·1	51	0·5
4	0·0	16	1·8	28	0·4	40	0·1	52	0·55
5	0·0	17	1·2	29	0·25	41	0·1	53	1·0
6	0·7	18	1·6	30	0·2	42	0·15	54	1·2
7	1·0	19	1·2	31	0·15	43	0·15	55	1·25
8	3·8	20	1·0	32	0·1	44	0·2	56	1·0
9	3·0	21	0·6	33	0·1	45	0·25	57	1·5
10	2·0	22	0·6	34	0·0	46	0·35	58	4·0
11	2·0	23	0·3	35	—	47	0·3	59	4·5
12	4·0	24	0·4	36	—	48	0·35	60	2·5

Remarks.

1. Time, 10.30 a.m. Air temperature, 58° F. Sky partly overcast by heavy clouds. Sea moderately rough; waves breaking. Slight haze noticeable. Signal first heard from navigating bridge but not on main deck 10 feet lower. 2. Signal just audible. 35. Signal just audible. 36. Time, 11.05 a.m. Sky clearing. Air temperature, 57° F. Ship turns at end of course. Signal just audible. 41. Sky clearing. Sea becomes smoother. Slight haze hanging low. 48–50. Rapid increase in audibility as estimated by ear. 55. Sun shining brightly and clouds clearing. Sea becomes much smoother 60. Time, 11.30 a.m. Air temperature, 58° F. Ship makes for Father Point wharf.

Control Observations.

End of Father Poin twharf.—Mean of three phonometer readings, 3·7. Echo, 18 seconds; maximum 4 seconds after termination of second blast.

Control station.—Phonometer reading, 7·3.

Mean air pressure operating diaphone, 18·2 lbs./sq. in. above atmospheric.

TABLE 6.—LONG RANGE ACOUSTIC SURVEY, September 4, 1913

Father Point Meteorological Observations.

Barometer, 30·26. Air temperature: dry bulb, 47° F.; wet bulb, 43° F.
Wind: steady. Velocity: 10–11 a.m., 5 miles per hour from N.W. 11–12 a.m., 3 miles per hour from the N.W.
Weather fairly clear. Clouds moving from W. Sky 50 per cent. clouded over.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	0·0	18	0·7	35	0·0	52	1·1	69	0·9
2	0·0	19	0·6	36	0·0	53	1·7	70	1·4
3	0·0	20	0·3	37	0·0	54	1·3	71	1·2
4	0·0	21	0·3	38	0·0	55	0·9	72	1·4
5	0·0	22	0·2	39	0·0	56	0·9	73	1·8
6	0·0	23	0·0	40	0·0	57	1·2	74	1·0
7	—	24	0·0	41	0·1	58	1·2	75	1·1
8	0·6	25	0·0	42	0·15	59	—	76	1·2
9	2·0	26	0·0	43	0·3	60	1·5	77	0·8
10	2·0	27	0·0	44	1·0	61	1·1	78	0·3
11	1·8	28	0·0	45	1·4	62	0·7	79	0·4
12	0·6	29	0·0	46	1·4	63	1·1	80	0·55
13	0·8	30	0·0	47	1·2	64	1·2	81	0·3
14	1·2	31	0·0	48	1·7	65	0·7	82	—
15	1·6	32	0·0	49	1·7	66	0·9	83	—
16	0·6	33	0·0	50	1·1	67	0·8		
17	1·1	34	0·0	51	1·0	68	0·7		

Remarks.

9.52 a.m. Left Rimouski wharf. Sea smooth. Sun shining brightly. Air temperature, 50° F.

1. Start of circular course at ½ mile distance from fog-signal station.

3. No signal heard. 4–6. Signal just audible. 12–13. Time at position 12, 10.21 a.m. Ship turning at end of course. Phonometer in acoustic shadow of deck house. 23. Signal just audible. Father Point wharf obstructing. 24–27. Signals barely audible. 28–37. Time at position 28, 10.38 a.m. Course along radius to 1 mile circular course. No signals heard along this course. 38. Signal just audible. 39. Signal not heard. 40. Signal just audible. 58–59. Time at position 58, 11.09 a.m. Ship turning back along 1 mile circular course. 82. Signal not heard. 83. Time 11.38 a.m. Ship turns back to Father Point wharf. Air temperature, 49° F.

Control Observations.

End of Father Point wharf.—Mean of six phonometer readings, 4·2. Echoes audible about 8 seconds and faint.

Control station.—Phonometer reading, 6·4.

Mean air pressure operating diaphone, 17·6 lbs./sq. in. above atmospheric.

TABLE 7.—LONG RANGE ACOUSTIC SURVEY, September 5, 1913.

Father Point Meteorological Observations.

Barometer, 29·97. Air temperature: dry bulb, 47° F.; wet bulb, 44° F. Wind: velocity, 10–11 a.m., 6 miles per hour from E.; 11–12 a.m., 3 miles per hour from E.

Weather, partly clear. Clouds moving from W. Sky 80 per cent. clouded over.

PHONOMETER READINGS.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	—	15	0·6	29	0·6	43	0·15	57	0·2
2	—	16	0·7	30	0·5	44	0·0	58	0·15
3	—	17	0·8	31	—	45	0·05	59	0·2
4	—	18	1·1	32	0·3	46	0·1	60	0·2
5	0·1	19	1·3	33	0·25	47	0·15	61	0·3
6	0·1	20	1·1	34	0·2	48	0·15	62	0·45
7	0·2	21	2·0	35	0·15	49	0·1	63	0·7
8	0·25	22	2·7	36	0·1	50	0·15	64	1·3
9	0·25	23	4·0	37	0·1	51	0·1	65	1·6
10	0·3	24	5·3	38	0·2	52	0·1	66	2·0
11	0·3	25	6·0	39	0·3	53	0·15		
12	0·3	26	3·0	40	0·1	54	0·25		
13	0·4	27	1·0	41	0·1	55	0·2		
14	0·5	28	0·4	42	0·1	56	0·3		

Remarks.

10.23 a.m. Left Rimouski wharf. Sea smooth, showing regions ruffled by variable breezes. Sky overcast by light fleecy clouds. Air temperature, 47° F.

1. Time, 10.53 a.m. Course set towards fog-signal. Signal not heard. Air temperature, 46° F.

2–4. Signals not heard.

14–16. Signals show marked increase in audibility. 25. Time, 11.16 a.m.; ship turning along new course. 44. Signals just audible. 45. Time, 11.38 a.m.; ship turning back along same course; air temperature, 48° F. 66. Time, 11.58 a.m. Ship turns in to Father Point wharf; air temperature, 52° F.

Control Observations.

End of Father Point wharf.—Mean of four phonometer readings, 4·2.

Control station.—Mean of four phonometer readings, 6·8.

Mean air-pressure operating diaphone, 18·3 lbs./sq. in. above atmospheric.

Table 8.—Long Range Acoustic Survey, September 9, 1913.

Father Point Meteorological Observations.

Wind : velocity, 10–11 a.m., 14 miles per hour from E.; 11–12 a.m., 14 miles per hour from E.
Weather partly clear. Clouds moving from N. Sky 80 per cent. clouded over.

Phonometer Readings.

Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.	Position No.	Phono-meter.
1	—	7	—	13	1·2	19	—	25	0·0
2	—	8	0·0	14	1·2	20	—	26	0·2
3	—	9	0·0	15	0·4	21	—	27	0·6
4	—	10	0·2	16	0·2	22	—	28	0·5
5	—	11	0·7	17	0·0	23	—	29	0·1
6	—	12	2·3	18	—	24	—	30	0·0

Remarks.

10.15 a.m. Left Rimouski wharf. Sea moderate; waves breaking. Sky overcast by light clouds. Air temperature, 52° F. 4. Signal distinctly heard from bridge but not from deck. 5–6. Inaudible from deck. 7. Signal distinctly heard from bridge but not from deck. 8. Signal first heard from deck. 9. Audible. 12. Time, 10.56 a.m.; ship turning back along same course. 13–14. Phonometer in acoustic shadow of deck house. 17–19. Inaudible. 20. Barely audible. 21. Inaudible. 22. Time, 11.06 a.m.; course back to fog-signal; signal barely audible. 23–24. Just audible. 25. Audible. 27. Time, 11.11 a.m.; course outwards from fog-signal. 30. Signal just audible. 31. Signal not heard. 32. Time, 11.17 a.m., course changed; signal not heard. 33–34. Inaudible. 35. Barely audible. 36. Time, 11·21 a.m.; course changed towards fog-signal; signal inaudible. 37. Inaudible. 38. Barely audible. 39–40. Just audible. 41. Time, 11.26 a.m.; air temperature, 53° F.

Control Observations.

End of Father Point wharf.—Mean of six phonometer readings, 2·5. No echoes heard.

Control station.—Mean of four phonometer readings, 7·5.

Mean air pressure operating diaphone, 18·3 lbs./sq. in. above atmospheric.

TABLE 9.—LONG RANGE ACOUSTIC SURVEY, September 10, 1913.

Father Point Meteorological Observations.

Wind: 10-11 a.m., velocity, 4 miles per hour from E. 11–12 a.m., 10 miles per hour from E.
Weather, clear. Clouds, none.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	0·15	14	0·3	27	0·0	40	—	53	1·3
2	0·15	15	0·2	28	0·0	41	—	54	1·0
3	0·06	16	0·1	29	—	42	—	55	4·0
4	0·1	17	0·1	30	—	43	—	56	4·2
5	0·1	18	0·1	31	—	44	0·3	57	2·6
6	0·3	19	0·05	32	—	45	0·3	58	1·6
7	0·35	20	0·15	33	—	46	1·0	59	1·6
8	0·25	21	0·0	34	—	47	1·2	60	0·9
9	0·6	22	0·0	35	—	48	0·6	61	0·4
10	0·7	23	0·05	36	—	49	0·9	62	0·3
11	0·7	24	0·0	37	—	50	0·8	63	0·1
12	0·7	25	0·0	38	—	51	1·5		
13	0·6	26	0·0	39	0·15	52	2·0		

Remarks.

10.38 a.m. Left Rimouski wharf. Sea smooth. Sky unclouded. Air temperature, 50° F.

1. Time, 10.51 a.m. Commencement of circular course at 1 mile. 6. Air temperature, 47° F. 9. Fog-signal in line with end of Father Point wharf. 26. Audible. 29–32. Barely audible. 33–34. Audible. 35. Time, 11.29 a.m. Course altered. Signal barely audible. 43. Time, 11.37 a.m. Commencement of circular course at ½ mile. 58. Ship enters acoustic shadow of wharf. 59. Wind drops to a light breeze. 63. Time, 11.56 a.m. End of circular course. Ship turns to Father Point wharf. Air temperature, 50° F.

Control Observations.

End of Father Point wharf.—Phonometer reading, 5·0. Slight echo audible.
Control station.—Phonometer reading, 9·3.

TABLE 10.—LONG RANGE ACOUSTIC SURVEY, September 12, 1913.

Father Point Meteorological Observations.

Wind: velocity, 10–11 a.m., 10 miles per hour from W.; 11–12 a.m., 9 miles per hour from W.
Weather, cloudy. Clouds almost stationary. Sky completely overcast.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	—	16	0·7	31	0·2	46	0·0	61	0·2
2	0·0	17	0·3	32	0·1	47	0·1	62	0·2
3	0·0	18	0·9	33	0·1	48	0·1	63	0·15
4	0·0	19	0·6	34	0·05	49	0·1	64	0·2
5	0·0	20	0·3	35	0·2	50	0·2	65	0·3
6	0·0	21	0·4	36	0·3	51	0·1	66	0·3
7	0·0	22	0·3	37	0·1	52	0·1	67	0·4
8	—	23	0·3	38	0·05	53	0·15	68	0·4
9	—	24	0·2	39	0·1	54	0·2	69	0·6
10	0·0	25	0·1	40	0·0	55	0·1	70	0·8
11	0·1	26	0·2	41	0·0	56	0·15	71	1·0
12	0·7	27	0·2	42	0·0	57	0·3	72	1·4
13	3·3	28	0·2	43	0·0	58	0·3	73	2·0
14	1·5	29	0·2	44	0·1	59	0·2		
15	2·1	30	0·1	45	0·1	60	0·15		

Remarks.

10.42 a.m. Left Rimouski wharf. Sea smooth. Sky completely overcast by heavy clouds. Air temperature, 52° F.

1. Time, 11.0 a.m. Signal first heard from deck. 2–3. Just audible. 4. Audible. 5-7. Just audible. 8. Inaudible. 9. Barely audible. 10. Audible. 14. Phonometer in acoustic shadow of deck house. 15. Time, 11.14 a.m. Ship turns to take up course away from fog-signal. 16–17. Phonometer in acoustic shadow of deck house. Echo audible for about 6 seconds 41. Time, 11.43 a.m. Ship turns back along same course. 71. Ship turns into Father Point wharf. Air temperature, 51° F.

Control Observations.

End of Father Point wharf.—Mean of five phonometer readings, 1·0.

Control station.—Phonometer reading, 3·9.

Mean air pressure operating diaphone, 22·6 lbs./sq. in. above atmospheric.

TABLE 11.—LONG RANGE ACOUSTIC SURVEY, September 16, 1913.

Father Point Meteorological Observations.

Barometer, 30·49. Air temperature: dry bulb, 52° F.; wet bulb, 48° F.
Wind: 9–10 a.m., velocity, 12 miles per hour from W.; 10–11 a.m., 13 miles per hour from W.
Weather, clear. Clouds, none.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	—	16	3·5	31	0·3	46	0·3	61	0·2
2	—	17	5·0	32	0·1	47	0·6	62	0·3
3	—	18	2·0	33	0·0	48	1·1	63	0·3
4	—	19	2·0	34	0·0	49	1·3	64	0·3
5	—	20	1·0	35	0·1	50	1·4	65	0·2
6	—	21	2·3	36	0·2	51	2·3	66	0·4
7	—	22	0·9	37	0·1	52	2·0	67	0·6
8	—	23	0·7	38	0·2	53	0·3	68	0·8
9	—	24	0·4	39	0·5	54	0·5	69	0·8
10	—	25	1·2	40	0·3	55	0·8	70	0·9
11	—	26	0·8	41	0·3	56	1·5	71	1·2
12	—	27	0·3	42	0·4	57	1·6	72	2·6
13	0·2	28	0·2	43	0·8	58	0·6		
14	1·0	29	0·3	44	0·8	59	0·3		
15	4·0	30	0·2	45	0·3	60	0·3		

Remarks.

9.27 a.m. Left Rimouski wharf. Sea moderate; waves breaking. Sky perfectly clear. Air temperature, 54° F.

1. Time, 9.42 a.m. Signal first heard. 2–10. Signals barely audible. 11. Just audible. 12. Audible. 18. Time, 9.59 a.m. Ship starts on course away from fog-signal. 33. Time, 10.17 a.m. Ship turns back along the same course. 45. Sky becomes slightly overcast. 51. Time, 10.35 a.m. Ship turns back along same course. 53. Phonometer in acoustic shadow of deck house. 62. Time, 10.47 a.m. Ship turns back towards fog-signal. 72. Ship turns into Father Point wharf. Air temperature, 54° F.

Control Observations.

End of Father Point wharf.—Mean of four phonometer readings, 1·5.

Control station.—Mean of four phonometer readings, 6·5.

Mean air pressure operating diaphone, 19·7 lbs./sq. in. above atmospheric.

TABLE 12.—LONG RANGE ACOUSTIC SURVEY, September 17, 1913.

Father Point Meteorological Observations.

Barometer, 30·14. Air temperature: dry bulb, 54° F.; wet bulb, 52° F.

Wind: 10–11 a.m., velocity, 11 miles per hour from W.; 11–12 a.m., 15 miles per hour from W.

Weather, cloudy. Clouds moving from W. Sky completely clouded over.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	0·2	14	0·8	27	2·0	40	0·0	53	0·6
2	0·2	15	2·0	28	0·5	41	—	54	0·7
3	0·3	16	2·3	29	1·8	42	—	55	0·8
4	0·2	17	0·9	30	1·8	43	—	56	0·7
5	0·1	18	1·6	31	1·6	44	0·0	57	0·8
6	0·3	19	1·0	32	0·9	45	0·0	58	0·7
7	0·35	20	0·6	33	0·9	46	0·0	59	0·6
8	0·5	21	0·6	34	0·3	47	0·0	60	0·6
9	0·7	22	—	35	0·3	48	0·0	61	0·5
10	0·8	23	1·6	36	0·3	49	0·1	62	0·6
11	2·3	24	0·9	37	0·2	50	0·3	63	1·2
12	2·1	25	0·8	38	0·0	51	0·5		
13	1·8	26	1·4	39	0·0	52	0·8		

Remarks.

10.29 a.m. Left Rimouski wharf. Sea smooth. Sky completely overcast. Smoke from ship hangs low. Air temperature, 56° F.

1. Time, 10.48 a.m. Ship commences circular course at ½-mile radius. 6. Ship clear of acoustic shadow of wharf. 12. Echoes marked, audible for 10 seconds. 21. Time, 11.08 a.m. Ship turns back along same course. 38–39. Signals audible. 40. Signal barely audible. 41–43. Ship turns outward from fog-signal to take up circular course at 1 mile radius. Signals inaudible. 44. Time, 11.32 a.m. Ship commences circular course. Signal inaudible. 45–46. Signals just audible. 47. Signal audible. 63. Time, 11.51 a.m. Ship turns into Father Point wharf. Air temperature, 54° F.

Control Observations.

End of Father Point wharf.—Mean of three phonometer readings, 1·8.

Control station.—Phonometer reading, 4·9.

Mean air pressure operating diaphone, 24·7 lbs./sq. in. above atmospheric.

TABLE 13.—LONG RANGE ACOUSTIC SURVEY, September 19, 1913.

Father Point Meteorological Observations.

Wind : 8-10 a.m., average velocity 2 miles per hour from W.

Weather, clear. No clouds.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	0·2	17	1·0	33	0·7	49	0·5	65	1·3
2	0·4	18	0·7	34	0·6	50	0·2	66	1·4
3	0·3	19	1·0	35	0·7	51	0·2	67	0·8
4	0·5	20	—	36	0·2	52	0·1	68	1·8
5	0·4	21	0·3	37	0·6	53	0·1	69	3·2
6	0·5	22	0·3	38	0·3	54	—	70	2·0
7	0·5	23	0·7	39	0·3	55	—	71	3·2
8	0·8	24	0·3	40	0·4	56	0·0	72	2·2
9	0·9	25	0·2	41	0·6	57	0·0	73	1·6
10	1·0	26	1·6	42	0·8	58	0·3	74	3·1
11	0·7	27	1·2	43	0·7	59	0·2	75	2·8
12	1·2	28	0·3	44	0·6	60	0·2	76	1·7
13	0·5	29	0·6	45	0·7	61	0·5		
14	0·9	30	0·4	46	1·1	62	1·0		
15	0·6	31	0·6	47	1·0	63	—		
16	—	32	1·3	48	0·6	64	0·6		

Remarks.

8.40 a.m., left Rimouski wharf. Sea smooth. Sky unclouded. Very light breeze. Air temperature, 59° F.

1. Time, 8.55 a.m. Commencement of circular course at 1 mile radius. 21. Time, 9.12 a.m. Course away from fog-signal. 26. Time, 9.18 a.m. Commencement of circular course at 2 miles radius. 54. Time, 9.48 a.m. Course towards fog-signal. Signal barely audible. 56. Signal just audible. 57. Audible. 63. Time, 9.58 a.m. Commencement of circular course at ½ mile radius. 68. Marked echo: audible for 10 seconds. 76. Time, 10.11 a.m. Course set towards Father Point wharf. Air temperature, 53° F.

Control Observations.

End of Father Point wharf.—Mean of four phonometer readings, 5·0. Echoes audible for 20 seconds.

Control station.—Phonometer reading, 6·8.

Mean air pressure operating diaphone, 24·7 lbs./sq. in. above atmospheric.

TABLE 14.—LONG RANGE ACOUSTIC SURVEY, September 20, 1913.

PHONOMETER READINGS.

Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.	Position No.	Phonometer.
1	—	21	0·7	41	0·4	61	3·2	81	0·3
2	0·0	22	0·4	42	0·2	62	3·0	82	0·5
3	0·0	23	0·3	43	0·25	63	3·0	83	0·6
4	0·05	24	0·3	44	0·15	64	2·4	84	1·0
5	0·6	25	0·2	45	0·2	65	3·2	85	0·9
6	0·5	26	0·3	46	0·5	66	2·6	86	0·5
7	1·0	27	0·2	47	0 1	67	4·0	87	1·2
8	1·0	28	0·1	48	0·25	68	4·5	88	0·9
9	5·5	29	0·1	49	1·1	69	4·7	89	1·2
10	—	30	0·05	50	1·2	70	5·0	90	1·2
11	2·3	31	0·0	51	0·6	71	1·2	91	1·6
12	2·0	32	0·0	52	1·4	72	0·6	92	2·4
13	1·2	33	0·0	53	1·2	73	—	93	2·4
14	2·0	34	0·3	54	1·6	74	0·6	94	1·8
15	0·9	35	0·3	55	1·2	75	0·6	95	2·0
16	1·0	36	0·3	56	1·0	76	0·3	96	1·6
17	0·9	37	0·2	57	1·4	77	0·6	97	1·6
18	0·7	38	0·2	58	3·2	78	0·4	98	0·6
19	0·4	39	0·15	59	2·9	79	0·7	99	—
20	0·4	40	0·2	60	2·5	80	0·3	100	0·6

Remarks.

10.13 a.m. Left Rimouski wharf. Sea smooth. Sky unclouded. Slight breeze from E. Air temperature, 52° F.

1. Signal first heard from bridge. 2. Signal first heard from deck: barely audible. 3. Audible. 12. Time, 10.35 a.m. Start of course away from fog-signal. 17. Echo audible about 25 seconds. 31–32. Audible. 33. Just audible. 40. Time, 11.06 a.m. Ship turns back along same course. 42. Ship stopped; fog-signal on port side. 43. Ship stopped; fog-signal straight ahead. 44. Ship stopped; fog-signal on starboard side. 45. Ship stopped; fog-signal straight ahead. 46. Ship starts in course towards Father Point. 67. Air temperature, 56° F. 70. Time, 11.40 a.m. Course altered to take up circular course at ½ mile radius. 71–73. Phonometer in acoustic shadow of deck house. 74. Time, 11.43 a.m. Commencement of circular course at ½ mile. 98. Ship enters acoustic shadow of wharf. 100. Time, 12.09 p.m. Course set for Father Point wharf. Air temperature 58° F.

Control Observations.

End of Father Point wharf.—Mean of two phonometer readings, 3·75.

Control station.—Mean of two phonometer readings, 7·1.

Mean air-pressure operating at conclusion of observations, 24·6 lbs./sq. in. above atmospheric.

NOTE.—Observations 42-45 were taken with a view to determining whether the effect of the ship's hull when presented broadside and bow-on was noticeable on the intensity of the sound as measured at the phonometer. It was concluded that within the limits of variation due to changing atmospheric conditions such an effect is not noticeable.

APPENDIX III.—ON THE THERMODYNAMIC MEASUREMENT OF ACOUSTIC EFFICIENCY.

(i.) GENERAL PROCEDURE IN TAKING OBSERVATIONS.

The construction of the open-wound resistance thermometers employed in measuring temperature differences is clearly shown in the Plate (iv.). That on the low-pressure side of the diaphone (S_0) was situated about 5 inches from the edge of the piston, while that on the high-pressure side (R) was situated in the large valve admitting the "sounding air," as shown diagrammatically in fig. 3. Electrical connection to the Wheatstone bridge was made through an automobile spark-plug inserted in the cover plate of the valve. At the beginning and end of a series of observations a test was made of the insulation of the wire grids. It was found that after a long series of observations the high-pressure thermometer became slightly damp if left in position over night, owing to the accumulation in the large valve, in which it was situated, of moisture brought over with the air from the storage tanks. It was thus necessary on commencing a test to thoroughly dry out the high-pressure thermometer; the insulation then remained satisfactory during the entire series of observations occupying about three hours.

During the series of observations the gas-engine operating the compressors were kept running continuously until the highest pressure to be employed in the tests had been attained. During this interval the mercury manometer connected to the storage tanks was read at known intervals, so that the rate of pressure increase could be determined at each pressure. The small relay-valve connected to the large valves admitting the "driving" and "sounding" air to the diaphone was operated by one of the observers (H. H. H.) to give a 6-second blast as determined by an accurate stop-watch. The same observer also noted accurately the fall of the mercury manometer in this interval. At the same time the writer noted the deflection of the galvanometer of the Wheatstone bridge to which the differential thermometers were connected Each observation was repeated, the battery current of the Wheatstone bridge being reversed in the interval. The mean pressure fall in the 6-second interval is entered in the accompanying tables together with the difference of resistances of the differential thermometers corresponding to the observed galvanometer deflections.

After a series of observations with the diaphone sounding has been taken, the diaphone piston was removed and three small pieces of rubber packing inserted between the down-stream face of the driving head and the opposite face of the cylinder. By means of a set-screw inserted in the centre of the cover-plate the piston as a whole was not only prevented from vibrating but could be moved forward slightly against the pressure of the rubber cushions until the opposing ports were in such a position that the pressure-fall of the manometer in 6 seconds was the same at a given pressure as when the diaphone was allowed to sound, indicating that the air consumption in the two cases was the same. This adjustment was made at about 20 lbs. pressure (atmospheric); an inspection of the series of pressures recorded in the accompanying tables shows that, except at some of the higher pressures, the two series agree fairly well throughout. Test No. 1 was carried out without any alteration of the existing adjustments. Test No. 2 was carried out with the large valve admitting sounding air set so that the air consumption was roughly halved. Before commencing Test No. 2, the diaphone piston was removed and carefully cleaned and lubricated. The sounding-valve was then adjusted until the diaphone emitted its clearest and smoothest note as judged by the ear. A comparison of the data given in Tests 1 and 3 shows that at the same pressure the rate of air consumption is somewhat greater in the latter. The acoustic efficiency is considerably improved in Test 3. Test 4 was carried out with the rate of air consumption about halved. In Test 5 the supply of sounding-air was turned off and the compressors stopped. The air from the storage tanks was then allowed to reciprocate the piston only. The fall of the pressure manometer in known intervals of time enables the rate of air consumption to be calculated. It will be noticed that only a comparatively small proportion of air is required to operate the diaphone piston. Unfortunately, temperature readings were not taken during this test. An upper limit to the rate at which energy is consumed in driving the piston may be made from the results of Test 4.

(ii.) MEASUREMENT OF PRESSURE AND AIR CONSUMPTION.

Pressure was measured by a mercury gauge connected to the storage tanks. During the 6-second blast required for the resistance thermometers to take up their final temperatures, the mercury column fell through a measured distance from which the air consumption could be calculated. Let the pressure fall from p_1 to p'_1. If ρ_1 and ρ'_1 be the corresponding densities, we have by BOYLE'S law

$$p_1 - p'_1 = (\rho_1 - \rho'_1)\,\mathrm{R}\Theta_1, \quad \text{(i.)}$$

Θ_1 being the temperature of the air in the storage-tanks and R the gas constant. If we denote by $\dot{\mathrm{M}}$ the rate of mass-flow of air during a blast of t seconds, and by V the total value of the storage tanks, we have

$$\dot{\mathrm{M}}t = \mathrm{V}\,(\rho_1 - \rho'_1). \quad \text{(ii.)}$$

Under standard conditions of pressure and temperature we have

$$p_0 = \rho_0\mathrm{R}\Theta_0, \quad \text{(iii.)}$$

so that from (i.), (ii.), and (iii.) we have for the rate of air consumption

$$\frac{\dot{\mathrm{M}}\Theta_1}{\rho_0} = \frac{(p_1 - p'_1)}{p_0}\,\frac{\mathrm{V}\Theta_0}{t}. \quad \text{(iv.)}$$

The volume of each of the storage tanks was calculated to be 282 cubic ft., so that

$$\mathrm{V} = 846 \text{ cubic ft.} = 2\cdot 39 \times 10^6 \text{ cm.}^3.$$

Throughout all the observations the duration of blast was $t = 6$ seconds. The pressure drop varied from 4 to 12 cms., and could be read with ease to half a millimetre. Allowance was made at each observation for the rate at which the pressure was increasing during the 6 seconds owing to the continuous operation of the compressors. The temperature of the air in the tanks was taken at 15° C. throughout, a value observed during one of the tests by the resistance thermometers. The air consumption in cubic feet per second under standard conditions of pressure and temperature is then given by (iv.) in the form

$$\frac{\dot{\mathrm{M}}}{\rho_0} = \frac{(p_1 - p'_1)}{76} \times \frac{846}{6} \times \frac{273^0}{288^0} = 1\cdot 76 \times (p_1 - p'_1) \text{ cubic ft./sec.} \quad \text{(v.)}$$

The output of a siren of unit efficiency as determined by formula (45) is given by

$$\dot{\mathrm{W}} = \mathrm{JC}_v\dot{\mathrm{M}}\Theta_1\left[1 - (p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right]. \quad \text{(vi.)}$$

Remembering that $\mathrm{JC}_v(\gamma - 1) = \mathrm{R} = p_0/(\rho_0\Theta_0)$, and making use of (iv.), we may write equation (vi.) in the form

$$\dot{\mathrm{W}} = \frac{(p_1 - p'_1)}{t}\cdot\frac{\mathrm{V}}{\gamma - 1}\left[1 - (p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right].$$

If $(p_1 - p'_1)$ be measured in centimetres of mercury, we have for numerical reduction

$$\dot{\mathrm{W}} = \frac{(p_1 - p'_1) \times 13\cdot 6 \times 981}{6 \times 0\cdot 4} \times \frac{2\cdot 39 \times 10^6}{7\cdot 46 \times 10^9}\left[1 - (p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right] \text{H.P.}$$

$$\dot{\mathrm{W}} = 17\cdot 8 \times (p_1 - p'_1) \times \left[1 - (p_0/p_1)^{\frac{\gamma-1}{\gamma}}\right] \text{H.P.} \quad \text{(vii.)}$$

In calculating the last factor we write for p_1 the mean pressure (above vacuum) between the beginning and end of the 6-second blast.

(ii.) ON THE MEASUREMENT OF TEMPERATURES.

The construction of the resistance thermometers employed in measuring the fall of air temperatures passing through the diaphone is briefly described in § 12. Although an attempt was made to make the high-pressure thermometer (of resistance R_0 at 0° C.) of exactly the same resistance as the low-pressure instrument (of resistance S_0 at 0° C.) it was found on making a careful measurement that

$$R_0 = 85{\cdot}044 \text{ ohms}, \qquad S_0 = 82{\cdot}095 \text{ ohms}.$$

The temperature coefficient of the iron wire employed as determined by Mr. A. A. SCOTT* was $\alpha = 0{\cdot}004964$. The thermometers R_0 and S_0 were connected by leads of heavy copper wire, of resistances 0·15 and 0·25 ohms respectively, so as to form two arms of a Wheatstone bridge. The ratio coils of the bridge were of resistances 100·84 and 100·81 ohms, sufficiently close together in value as to be considered equal. In series with S_0 was inserted a magnanin resistance box subdivided into tenths of an ohm. A portable Weston galvanometer of 217 ohms resistance and sensitivity of 10^{-6} amperes was employed to determine the balance of the Wheatstone bridge. In taking readings of temperature differences with the diaphone sounding and silent, a rough balance was obtained by adjusting the resistance box to the nearest tenth ohm and interpolating from the galvanometer deflection. If $\delta\theta$ be the temperature difference between the thermometer wires when the diaphone is sounding, and $\delta\theta'$ that when the diaphone is silent, corresponding to resistances s and s' required to balance the bridge in each case, we easily prove that

$$\delta\theta - \delta\theta' = -\frac{(R_0 - S_0)}{S_0}(\theta_1 - \theta'_1) + \frac{s - s'}{\alpha s_0}, \quad \ldots \ldots \ldots \quad \text{(viii.)}$$

θ_1 and θ'_1 being the temperatures of the thermometer R_0 when sounding and silent respectively. The first term represents the small correction arising from the inequality of resistance of the two thermometers. As the series of observations with the diaphone sounding and silent were taken immediately following one another, θ_1 and θ'_1 are assumed to be so nearly equal that this correction term may be neglected. We thus calculate the difference of the temperature differences of the two thermometers under conditions "sounding" and "silent" from the formula

$$\delta\theta - \delta\theta' = \frac{s - s'}{82{\cdot}095 \times 0{\cdot}004964} = 2{\cdot}46\,(s - s'). \quad \ldots \ldots \ldots \quad \text{(ix.)}$$

From formula (44) we may calculate the acoustic output of the diaphone from the formula

$$\begin{aligned} \dot{w} &= JC_v\dot{M}\,(\Theta_1 - \Theta) \\ &= \frac{(p_1 - p'_1)}{t}\,\frac{V}{\gamma - 1}\,\frac{(\Theta_1 - \Theta)}{\Theta_1}. \quad \ldots \ldots \ldots \quad \text{(x.)} \end{aligned}$$

We have seen from the discussion of § 12 that to a tolerable order of accuracy we may identify the actual temperature drop $(\Theta_1 - \Theta)$ in the diaphone when sounding with the observed difference of temperature differences of the thermometer wires $(\delta\theta - \delta\theta')$, (following the notation of (viii.) above). Inserting numerical values in (x.) we may thus write for purposes of computation, taking $\Theta_1 = 288°$ A.,

$$\dot{w} = 17{\cdot}8 \times (p_1 - p'_1)\,\frac{(\delta\theta - \delta\theta')}{288°}\ \text{H.P.} \quad \ldots \ldots \ldots \quad \text{(xi)}$$

In the diaphone actually tested the exhaust from the "driving head" passed into the resonator so that the estimate (xi.) includes the work required to operate the diaphone piston. This includes not only the work required to overcome friction but also a small portion of energy converted into sound. The former is

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[*] SCOTT, A. A., "A Study of Iron Wire for Electrical Resistance Thermometers," 'Trans. Roy. Soc. of Canada,' vol. VII., Third Series, 1913.

converted into heat, a large part of which is returned to the air, passing through the piston, and therefore does not contribute to the temperature drop of formula (xi.). As has already been mentioned, the frequency does not alter very greatly with the operating pressure, while the amplitude of vibration cannot vary between very wide limits if the valve-system of the driving head is to produce reciprocating motion at all. A reference to observation 1 of Test 4, at reduced air consumption, gives for the total power consumed in driving the piston and emitting sound the value 0·06 H.P. We are thus justified in estimating that throughout the entire range of operating pressures not more than 1/10 H.P. is required to reciprocate the diaphone piston. To this order of accuracy the power expenditure $\dot{w}$ calculated from (xi.) may be attributed to external work being propagated away in the form of sound-waves.

Test No. 1. September 13, 1913.

No. of observation.	Mean pressure above atmosphere. cm. mercury.	Pressure drop in 6 seconds.		Pressure increase in 6 seconds due to compressors. cm. mercury.	Mean pressure drop in 6 seconds. cm. mercury ($p_1-p'_1$).	Resistance change of differential thermometers, sounding and silent. ($s-s'$). ohms.
		Sounding. cm. mercury.	Silent. cm. mercury.			
1	50·8	3·7	3·35	1·0	4·5	0·57
2	60·5	4·2	4·1	0·95	5·1	0·80
3	70·1	4·5	4·85	0·9	5·6	0·95
4	79·8	5·2	5·55	0·85	6·2	1·05
5	89·7	5·55	5·8	0·8	6·5	1·20
6	99·1	6·3	6·9	0·8	7·4	1·40
7	103·0	6·5	7·1	0·75	7·55	1·40
8	109·0	7·1	7·35	0·75	8·0	1·31
9	118·6	7·5	8·1	0·75	8·55	1·28
10	128·2	7·9	8·9	0·75	9·15	1·23
11	137·5	9·1	10·15	0·75	10·4	1·14

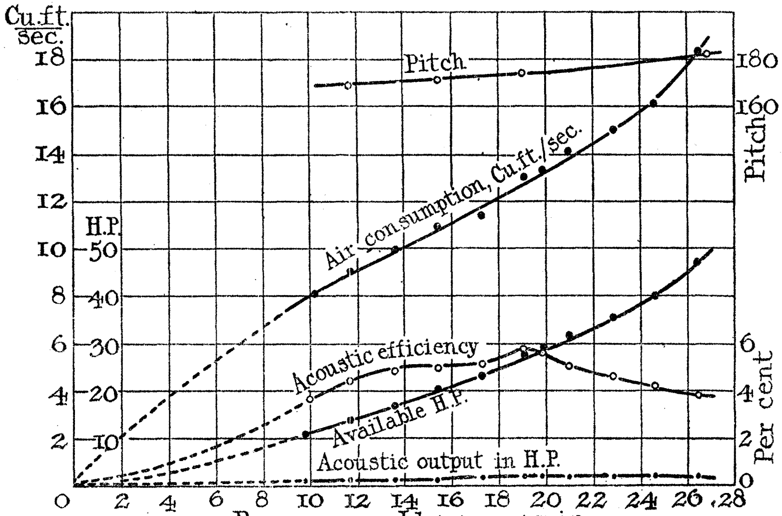

Fig. (i.). Characteristics of the diaphone.
Results of Test 1, September 13, 1913. Air consumption normal.

TEST No. 1 (continued).

No. of observation.	Mean pressure above atmosphere. lbs./sq. in.	Air consumption in cubic feet per second.	Maximum power possible in H.P. (W).	Temperature differences, sounding and silent ($\delta\theta - \delta\theta'$).	Power emitted as sound and consumed in driving piston in H.P. (w).	Acoustic efficiency ($\eta = w/W$).
				° C.		
1	9·8	7·9	10·9	1·40	0·39	0·036
2	11·7	9·0	13·9	1·97	0·62	0·044
3	13·6	9·9	16·9	2·34	0·81	0·048
4	15·4	10·9	20·5	2·58	0·99	0·049
5	17·3	11·4	23·1	2·95	1·19	0·051
6	19·1	13·0	27·9	3·44	1·57	0·057
7	19·9	13·3	29·2	3·44	1·60	0·056
8	21·0	14·1	31·9	3·22	1·60	0·050
9	22·9	15·0	35·8	3·15	1·66	0·046
10	24·7	16·1	40·0	3·03	1·70	0·042
11	26·5	18·3	47·3	2·80	1·80	0·038

TEST No. 2. September 15, 1913.

No. of observations.	Mean pressure above atmosphere. cm. mercury.	Pressure drop in 6 seconds.		Pressure increase in 6 seconds due to compressors. cm. mercury.	Mean pressure drop in 6 seconds. cm. mercury. ($p_1 - p'_1$).	Resistance change of differential thermometers, sounding and silent. ($s - s'$). ohms.
		Sounding. cm. mercury.	Silent. cm. mercury.			
1	51·6	1·75	1·45	1·05	2·1	0·40
2	61·5	2·0	1·8	1·0	2·9	0·63
3	71·5	2·2	2·25	0·9	3·1	0·70
4	81·2	2·8	2·7	0·9	3·6	1·03
5	91·1	2·65	2·95	0·9	3·6	0·96
6	100·8	3·1	3·25	0·85	4·0	1·04
7	110·7	3·8	3·7	0·8	4·6	1·00
8	120·5	4·2	3·8	0·7	4·7	0·67
9	130·4	4·5	4·25	0·7	5·1	0·71
10	140·1	5·1	4·8	0·7	5·7	0·72

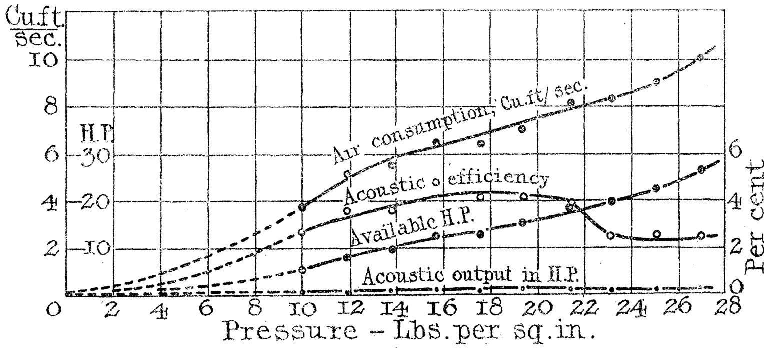

Fig. (ii.). Characteristics of the diaphone.
Results of Test 2, September 15, 1913. Air consumption halved by throttling.

TEST No. 2 (continued).

No. of observations.	Mean pressure above atmosphere. lbs./sq. in.	Air consumption in cubic feet per second.	Maximum power possible in H.P. (W).	Temperature differences, sounding and silent. $(\delta\theta-\delta\theta')$.	Power emitted as sound and consumed in driving piston in H.P. (w).	Acoustic efficiency. $(\eta=w/\mathrm{W})$.
				° C.		
1	10·0	3·7	5·1	0·98	0·13	0·026
2	11·9	5·1	8·0	1·55	0·28	0·035
3	13·8	5·5	9·5	1·72	0·33	0·035
4	15·7	6·4	12·2	2·53	0·57	0·047
5	17·6	6·4	12·9	2·36	0·53	0·041
6	19·4	7·0	15·3	2·56	0·63	0·041
7	21·4	8·1	18·7	2·46	0·71	0·038
8	23·2	8·3	19·9	1·65	0·48	0·024
9	25·1	9·0	22·4	1·75	0·55	0·025
10	27·0	10·0	26·4	1·77	0·62	0·024

TEST No. 3. September 16, 1913.

No. of observations.	Mean pressure above atmosphere. cm. mercury.	Pressure drop in 6 seconds.		Pressure increase in 6 seconds due to compressors. cm. mercury.	Mean pressure drop in 6 seconds. cm. mercury. $(p_1-p'_1)$.	Resistance change of differential thermometers, sounding and silent. $(s-s')$. ohms.
		Sounding. cm. mercury.	Silent. cm. mercury.			
1	38·5	3·7	3·7	1·1	4·9	0·58
2	50·5	4·0	4·0	1·0	5·1	1·16
3	60·3	4·4	4·2	0·9	5·3	1·31
4	70·0	5·0	4·9	0·9	5·85	1·46
5	79·8	5·6	5·6	0·8	6·5	1·59
6	89·6	6·0	6·0	0·8	6·8	1·83
7	99·3	6·7	6·8	0·8	7·55	2·05
8	109·0	7·1	6·9	0·8	7·8	1·90
9	118·8	7·7	7·5	0·8	8·4	1·66
10	128·6	8·0	8·2	0·7	8·9	1·25
11	138·2	8·8	9·0	0·7	9·7	0·82
12	148·0	9·3	10·3	0·7	10·5	0·64

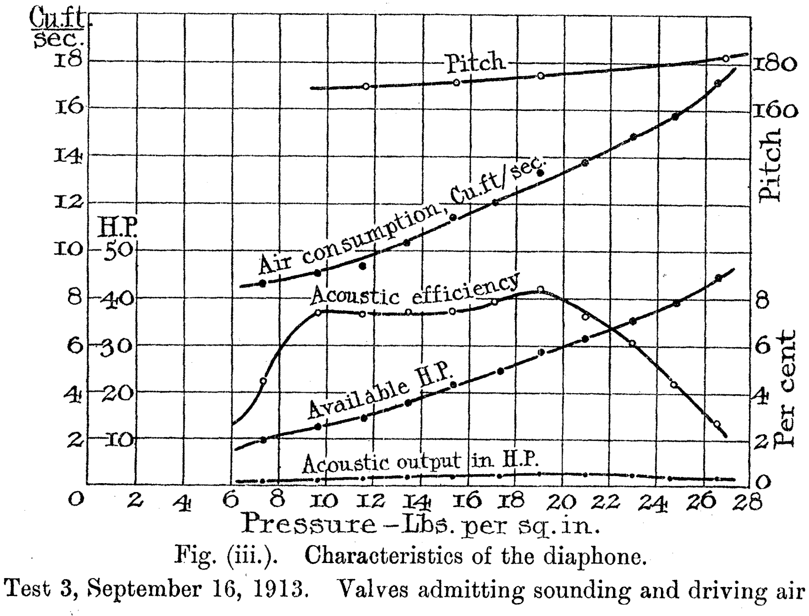

Fig. (iii.). Characteristics of the diaphone.

Results of Test 3, September 16, 1913. Valves admitting sounding and driving air re-adjusted.

TEST NO. 3 (continued).

No. of observations.	Mean pressure above atmosphere. lbs./sq. in.	Air consumption in cubic feet per second.	Maximum power possible in H.P. (W).	Temperature difference, sounding and silent. $(\delta\theta - \delta\theta')$.	Power emitted as sound and consumed in driving piston in H.P. (w).	Acoustic efficiency. $(\eta = w/W)$.
				° C.		
1	7·4	8·6	9·7	1·43	0·43	0·044
2	9·7	9·0	12·3	2·85	0·90	0·073
3	11·6	9·3	14·5	3·22	1·06	0·073
4	13·5	10·3	17·7	3·59	1·30	0·074
5	15·4	11·4	21·4	3·91	1·57	0·074
6	17·2	12·0	24·2	4·50	1·88	0·078
7	19·1	13·3	28·5	5·04	2·36	0·083
8	21·0	13·7	31·1	4·67	2·25	0·072
9	23·0	14·8	35·2	4·08	2·11	0·061
10	24·8	15·7	39·0	3·08	1·69	0·043
11	26·6	17·1	44·3	2·02	1·21	0·027
12	28·6	18·5	49·5	1·57	1·01	0·020

TEST NO. 4. September 16, 1918.

No. of observation.	Mean pressure above atmosphere. cm. mercury.	Pressure drop in 6 seconds.		Pressure increase in 6 seconds due to compressors. cm. mercury.	Mean pressure drop in 6 seconds cm. mercury. $(p_1 - p'_1)$.	Resistance change of differential thermometers, sounding and silent. $(s - s')$ ohms.
		Sounding. cm. mercury.	Silent. cm. mercury.			
1	40·0	0·85	0·65	1·05	1·8	0·22
2	51·7	1·6	1·6	1·0	2·6	0·62
3	61·6	1·85	1·95	0·9	2·8	0·94
4	71·4	2·3	2·25	0·9	3·2	1·08
5	81·3	2·55	2·55	0·8	3·35	1·25
6	91·1	2·9	3·0	0·8	3·75	1·35
7	100·8	3·6	3·55	0·8	4·40	1·44
8	110·7	3·8	3·7	0·8	4·55	1·49
9	120·5	4·25	4·0	0·75	4·85	1·08
10	130·4	4·6	4·3	0·7	5·15	0·89
11	140·1	5·05	5·0	0·7	5·75	0·87
12	149·6	(6·1)	5·9	0·7	6·7	0·84
13	159·1	7·1	6·8	0·7	7·65	0·99

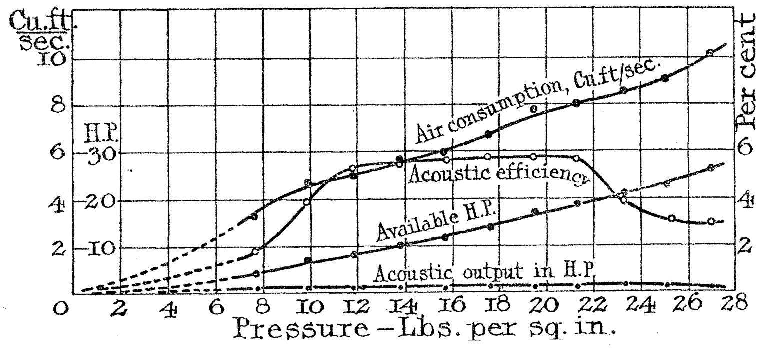

Fig. (iv.). Characteristics of the diaphone.

Results of Test 4, September 16, 1913. Conditions as in Test 3, with air consumption halved by throttling.

Test No. 4 (continued).

No. of observation.	Mean pressure above atmosphere. lbs./sq. in.	Air consumption in cubic feet per second.	Maximum power possible in H.P. (W).	Temperature difference, sounding and silent $(\delta\theta - \delta\theta')$.	Power emitted as sound and consumed in driving piston in H.P. (w).	Acoustic efficiency $(\eta = w/W)$.
				° C.		
1	7·7	3·2	3·6	0·54	0·06	0·017
2	9·9	4·6	6·3	1·52	0·24	0·038
3	11·8	4·9	7·7	2·31	0·40	0·052
4	13·8	5·6	9·8	2·66	0·53	0·054
5	15·7	5·9	11·2	3·08	0·63	0·056
6	17·6	6·6	13·5	3·32	0·77	0·057
7	19·5	7·7	16·8	3·54	0·96	0·057
8	21·3	8·0	18·3	3·66	1·03	0·056
9	23·3	8·5	20·5	2·66	0·80	0·039
10	25·1	9·0	22·8	2·19	0·70	0·031
11	27·0	10·1	26·3	2·14	0·76	0·029
12	28·9	11·8	31·9	2·07	0·86	0·027
13	30·7	13·4	37·6	2·44	1·15	0·031

Test No. 5. Air Consumed in Driving Cylinder.

No. of observations.	Mean pressure above atmosphere. cm. mercury.	Pressure drop in time t. $(p_1 - p_1)$. cm. mercury.	t. seconds.	Mean pressure above atmosphere. lbs./sq. in.	Air consumption. cubic feet/seconds.
1	47·0	12·0	260·6	9·1	0·48
2	58·2	10·3	183·4	11·2	0·59
3	68·3	10·0	161·4	13·1	0·65
4	78·1	9·7	142·6	15·1	0·72
5	88·0	10·0	129·8	17·0	0·81
6	98·0	10·0	118·2	18·9	0·89
7	108·0	10·0	109·6	20·8	0·96
8	118·0	10·0	93·2	22·8	1·13
9	128·1	9·8	93·4	24·7	1·11
10	138·0	10·0	78·0	26·6	1·36
11	148·0	9·5	63·2	28·6	1·58
12	157·9	10·2	58·2	30·5	1·81

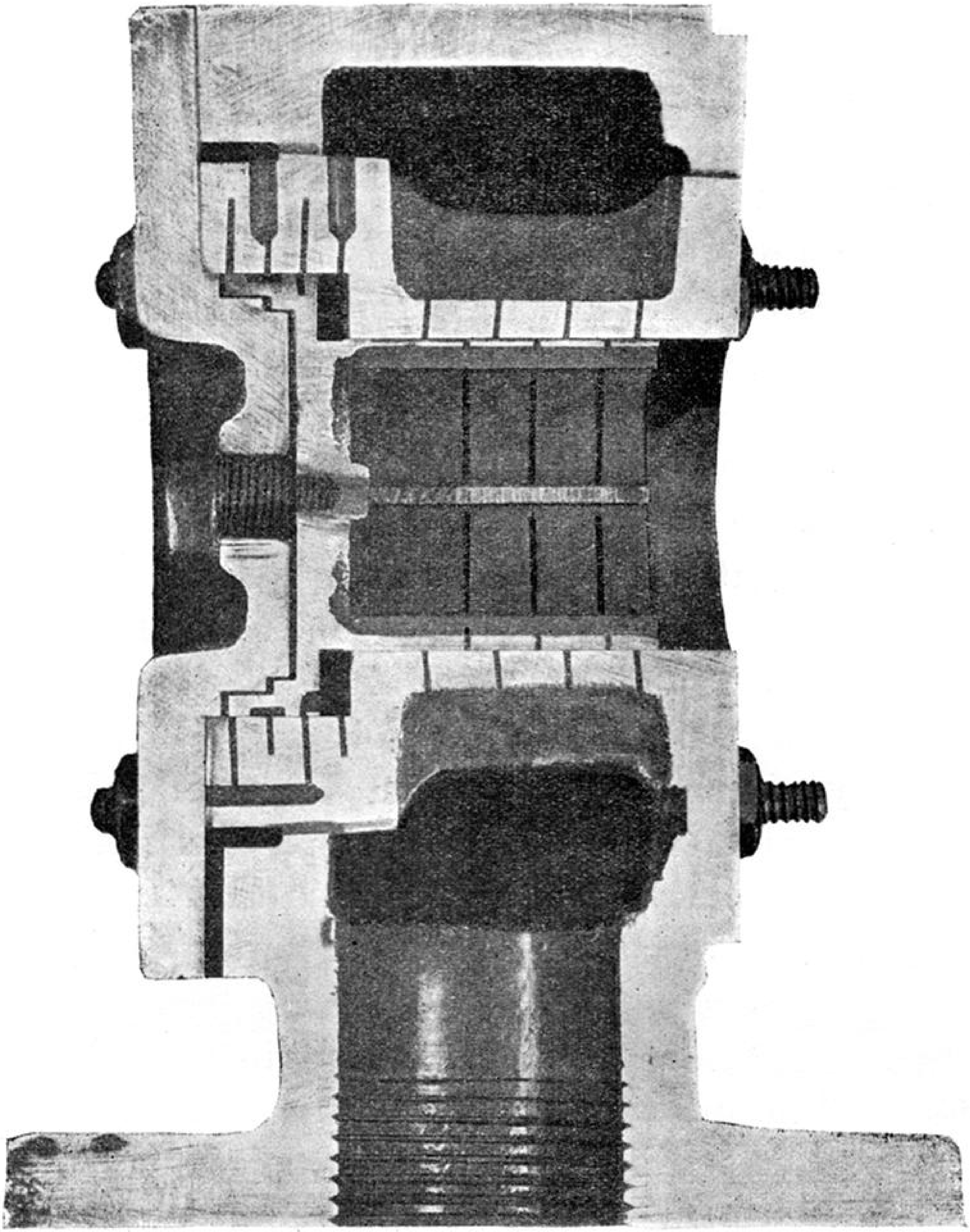

Fig. 1. Small model of the diaphone sectioned to show details of construction.

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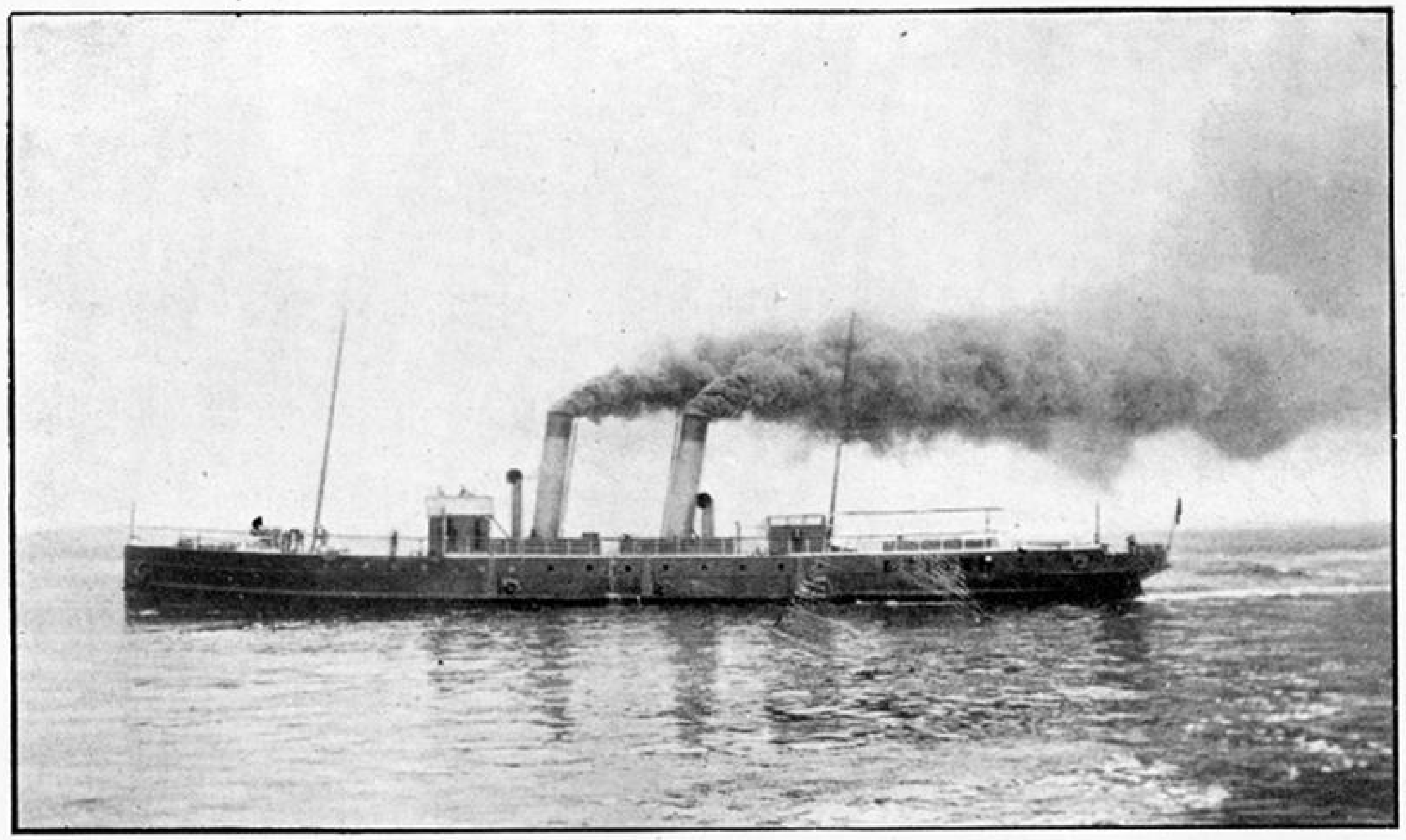
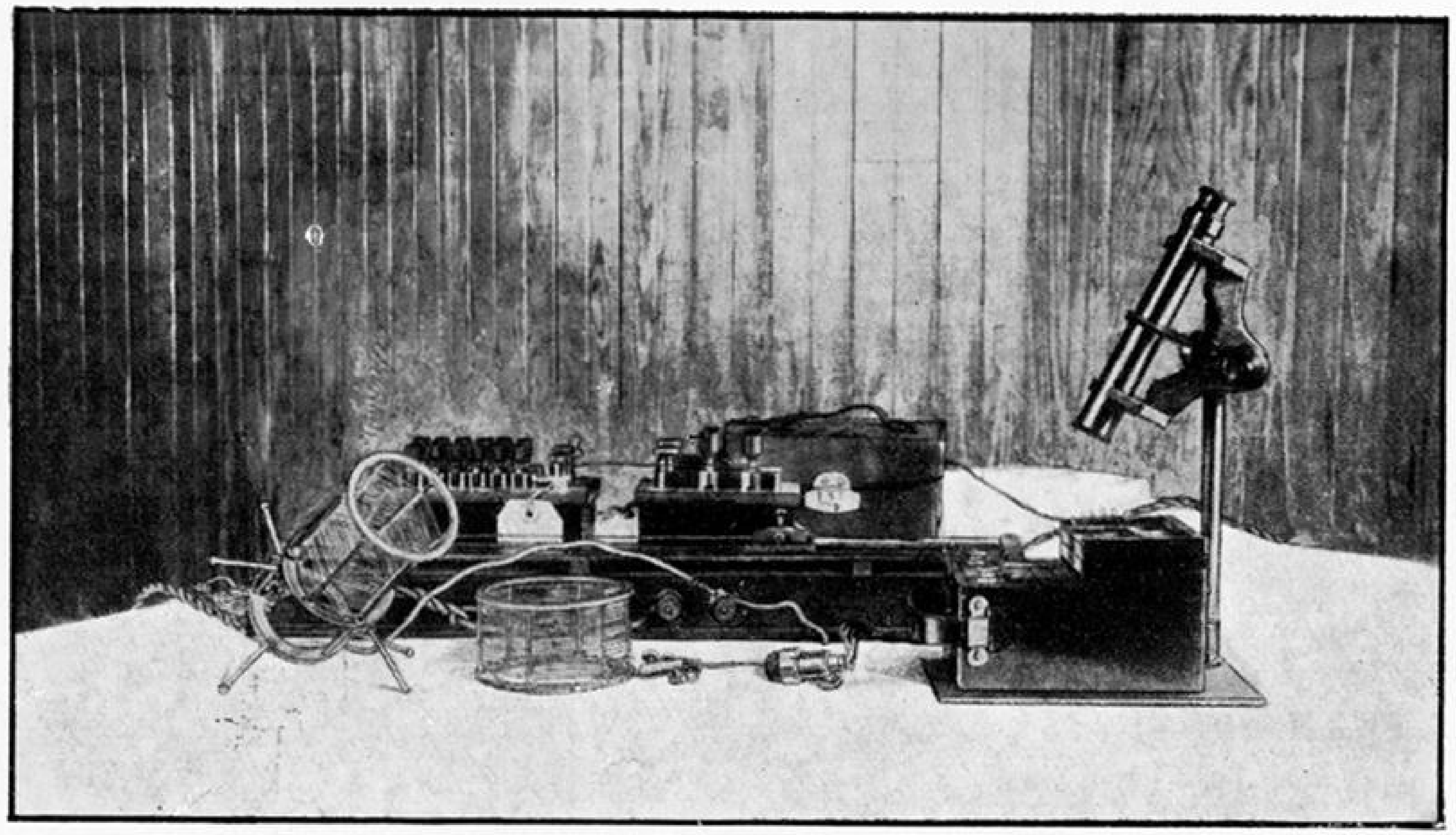
(i.) Webster phonometer mounted on a theodolite tripod. Building on the left is the fog-signal station, showing trumpet of diaphone. Father Point lighthouse in the background. The results obtained are shown graphically in Chart 1.

(ii.) Acoustic survey carried out from a ship's boat. The phonometer is shown mounted at the bow of the boat. The results obtained are shown graphically in Chart 2.



(iii.) C.G.S. "Lady Evelyn." From this ship were taken the phonometer observations for the long range acoustic surveys, the results of which are shown graphically in Charts 3 to 14.



(iv.) Apparatus for the thermal measurement of the acoustic output of diaphone. The skeleton construction of the iron-wire resistance thermometers is clearly shown.