Pyrotechnic Whistles

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Introduction

The fact that certain pyrotechnic compositions when pressed into a tube and ignited burn with a loud whistling noise has been known and used by firework manufacturers for many years. The two compositions most widely employed appear to be (a) a mixture of dry powdered potassium picrate and potassium nitrate in the proportions of about 60/40 and (b) a mixture of powdered gallic acid and potassium chlorate in the proportions 25/75. Whistling compositions have occasionally been used for military purposes. Thus in World War II the Germans had a whistling cartridge (pfeif-patrone) for signaling and the Canadians used a whistling thunderflash for training purposes. In October, 1943, the author was instructed to investigate in collaboration with the Admiralty the use of pyrotechnic whistles burning under water as a possible counter measure to the acoustic homing torpedo then being used by the Germans. As little was known about the factors influencing the intensity and frequency of the sound made by pyrotechnic whistles or their mode of action an investigation into this subject was made and is described in the present paper. A number of measurements were also made on pyrotechnic whistles burning under water, but as they are mainly of acoustical interest only, they will be dealt with very briefly.

Measurement of Frequency

The measurement of the main component of the frequency was accomplished by means of a Rothermel BR 2S crystal microphone connected through an amplifier detector and driver amplifier to the Y-plates of a cathode ray tube. The X-plates of the tube were connected to an amplified time base. This time base was usually set to traverse the tube in about one five hundredth of a second by connecting the input from a thousand cycle tuning fork oscillator to the Y-plates and adjusting so as to get the required number of waves on the screen. The time base could be locked to the incoming signal from the microphone so that the nearest whole number of waves appeared on the screen. These waves could be counted and the fundamental frequency of the whistle determined. To determine the frequency more exactly or to examine the wave-form for the presence of harmonics the time base was not used but the wave-form was obtained by photographing the movement of the oscillograph spot on a rotating drum camera. To get a record of the wave-form for an appreciable length of time the shift knob on the oscillograph was turned so as to move the spot across the screen while taking the record so that a spiral trace was obtained. Immediately before or immediately after taking a record a time base was put on near one edge of the paper by means of the fork oscillator.

Measurement of Intensity

The amplifier detector unit to which the crystal microphone was connected contained a rectification stage which could be switched into the circuit when it was desired to measure the intensity. The output in millivolts was then proportional to the root mean square pressure in the sound wave and the intensity was proportional to the square of this value. The instrument was fitted with a sensitivity switch so as to cover different ranges of intensity, the output was fed into an oscillograph unit and the motion of the spot photographed on a drum camera. A record from a time marker giving ten marks per second was obtained at the same time. The amplifier detector was fitted with a calibrating switch which enabled a known voltage to be applied to the oscillograph where the deflection of the spot was recorded by the drum camera. Since the sensitivity of the microphone and the characteristics of the instrument were known, the value of the calibrating pulse in terms of RMS (root mean square) dynes/cm^2 could be calculated. The output from whistles of the coachman's lamp type (see below) was usually fairly constant, and the mean intensity could then be taken as proportional to the mean value of the root mean square pressure which was obtained by integrating the record with a planimeter.

It was found that, to obtain consistent results, measurements designed to investigate any particular effect had to be carried out on the same day under the same conditions; also if the effect of some physical factor such as tube diameter was being investigated for a particular composition then the composition used had to be all from the same batch and preferably consolidated at the same time. Similarly the ingredients of compositions containing varying proportions had to come from the same batch. Unless all these precautions were taken, inconsistencies which might amount to several hundred per cent were likely to be experienced. All measurements described in this paper were made over grassland with the micro-phone and whistle at a height of about 5 ft above the ground.

Variation of Frequency with Tube Length

When a tube filled with a whistling composition is burned in air it is obvious to the ear that the frequency of the main component of the sound falls continuously as the length of the tube above it increases. To study this effect quantitatively it is necessary, or at any rate very convenient, to use whistles in which the length of the tube above the burning composition remains constant. This is most easily achieved by using a principle similar to that employed in the old-fashioned coachman's lamp and can be most readily understood by reference to Figure 1. It was necessary to coat the pellets of whistling composition very carefully in order to prevent ignition down the sides and consequent explosion. The method which was extensively used for this purpose consisted of coating the cylindrical surface of the pellets with three coats of enamel paint followed by two layers of insulating tape and then a layer of lassolastic tape to give a smooth finish. In addition, a layer of clay was usually pressed at the bottom of the pellet to prevent ignition at the base end. The three knife edges against which the pellet pressed were necessary to cut through the charred remains of the coating materials.

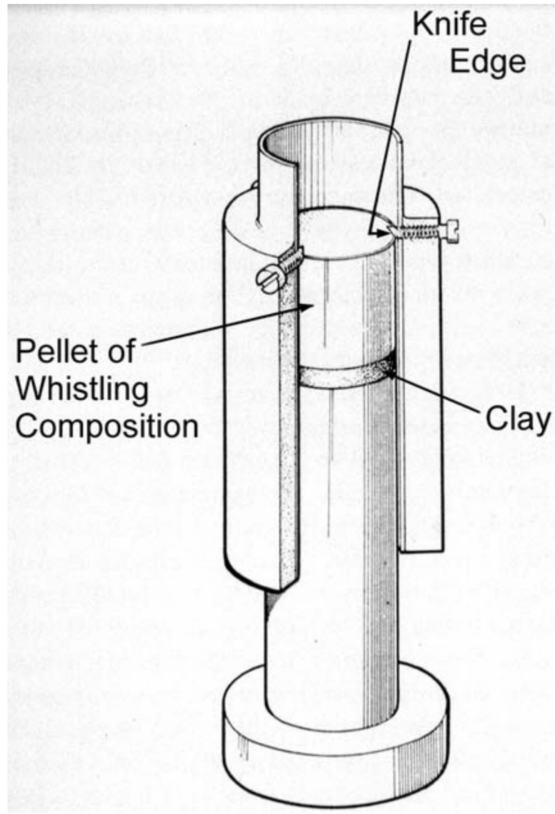

Figure. 1. Constant frequency whistle using principle of coachman's lamp.

The determination of the frequencies produced by different tube lengths were carried out with the following composition (120 BS means that the powdered material had all passed through a 120 BS sieve).

Potassium benzoate, 120 BS	30 parts
Potassium perchlorate, 120 BS	70 parts

Two diameters of steel tubing were used and the result are shown in Figure 2. It will be seen that except for short lengths the frequency is approximately inversely proportional to the length of tube above the composition. The acoustic system is thus similar to that in an open organ pipe. It is a coupled system in which the frequency is controlled mainly by the length of the resonance tube above the burning composition. The frequency is not exactly inversely proportional to the length of tube, but there is an end correction as with an organ pipe. This end effect becomes of major importance for short lengths of tube. For an organ pipe the correction for a tube of radius R is 0.786R (Helmholtz) or 0.824R (Rayleigh), the tube being assumed to have an infinite flange. For pyrotechnic whistles the correction is more complicated, but it is greater, the greater the diameter of the tube. When the length of the tube falls below a certain value, the composition ceases to whistle. The critical whistling frequency varies somewhat with the composition. For the composition containing 30 parts of potassium benzoate and 70 parts of potassium perchlorate this frequency is about 5000 cycles/sec and for most other compositions is below this value. No composition which will whistle at an appreciably higher frequency than this is known to the author.

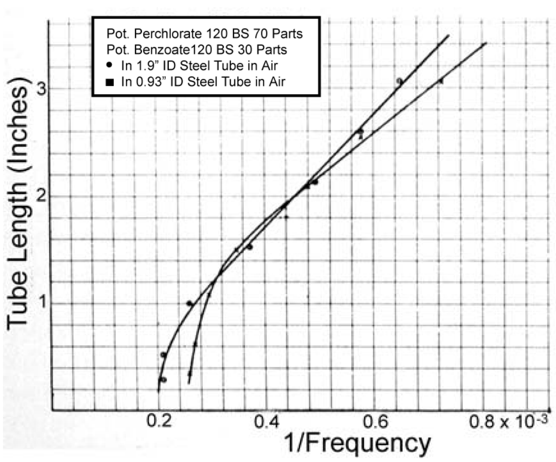

Figure. 2. Effect of tube length on frequency.

Variation of Frequency with Composition

Since the resonating frequency of a tube is dependent on the velocity of sound in the gas in the tube it is to be expected that any change in the ingredients or in the proportion of the ingredients of a whistling composition will lead to a change in the frequency given by a definite tube length, because the composition of the products of combustion and probably the temperature will be different. This variation has been experimentally verified. For example a composition consisting of 70 parts of potassium 2:4 dinitrophenate and 30 parts of potassium nitrate gave a frequency of 2380 cycles/sec when burned in a coachman's lamp type tube, 0.93 inches in diameter and with 1.52 inches of tube above the burning surface. Whilst a composition consisting of 70 parts of potassium perchlorate and 30 parts of potassium benzoate when burned under the same conditions gave a frequency of 2700 cycles/sec.

Effect of Frequency on Rate of Burning

If a composition is ignited in a tube which is too short for it to whistle in, it burns at a rate appreciably greater than it would do if it whistled. This effect can be simply demonstrated by pressing 4 g of 70/30 potassium perchlorate/ potassium benzoate composition already referred to into each of two half-inch diameter tubes three inches long under a dead load of two tons, so that the composition is 0.10 inch down the tube at the one end (Figure 3). If the two tubes are lit from different ends, it will be found that the tube which whistles (i.e., the one in which the composition was ignited at the end furthest in the tube) takes about 1.4 times as long to burn as the one which does not whistle. Some such effect as this might be expected since, as will be shown later, the whistling composition in all probability stops and starts burning alternately so that it is burning for only a part of the time. The difference between the two rates is not nearly so great when the whistle is burning at high frequency. The marked difference between the whistling and non whistling flames is apparent from the photograph shown in Figure 4.

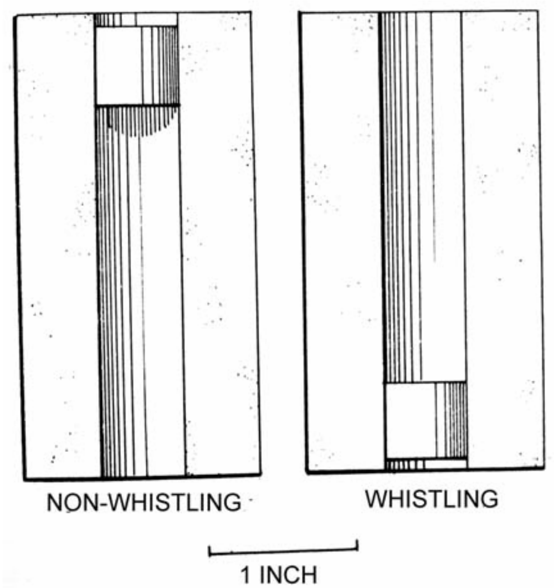

Figure 3. Experiment to show that a whistling composition burns faster under conditions when it cannot whistle.

The effect of the frequency of the whistle on the rate of burning of the composition was investigated by burning short lengths at various depths in a 0.93 inch diameter steel tube. The frequency corresponding to any particular depth was taken as the mean between the values corresponding to the top and bottom of the composition determined from the curve in Figure 2. The results are plotted in Figure 5. It will be seen that the composition burns fastest at high frequencies and that the rate of burning changes much more slowly with frequency at low frequencies.

Acoustic Output of Pyrotechnic Whistles

If the RMS pressure is measured at a considerable distance from the source, the energy flow per unit of surface can be regarded as being the same as for a plane wave, i.e. = ½(δp max)$^2/\rho c$, where δp max is the maximum variation in pressure in the wave, ρ is the density of the air and c the velocity of sound in air.

The total energy output of the whistle, if it is assumed that all the sound which strikes the

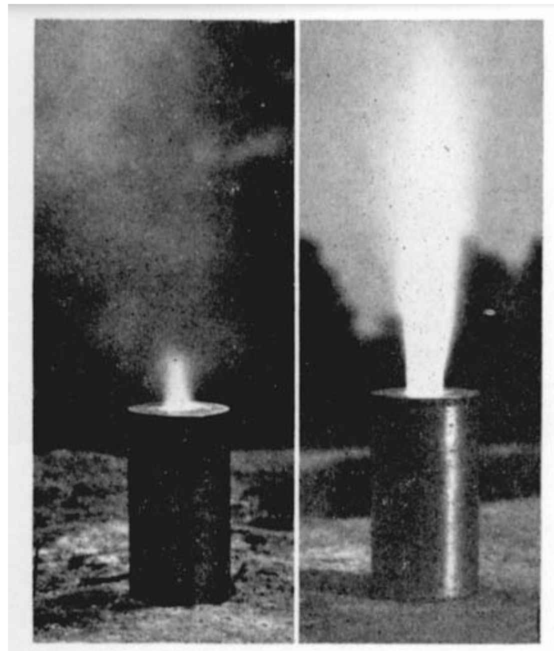

Figure 4. Photographs of whistling and non-whistling flames (Exposure time ca 1/50 sec). Left: Whistling. Right: Non-whistling.

ground is absorbed (which is not true, but the error introduced should be fairly constant)

$$= \frac{4\pi r^2 (\delta p \max)^2}{2\rho c}$$

It is the RMS pressure δp RMS which is actually measured, and since

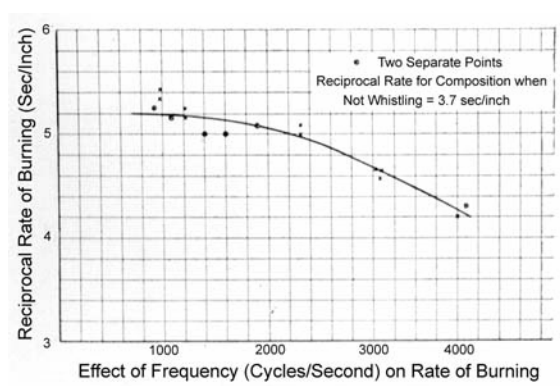

Figure 5. Effect of frequency (cycles/second) on rate of burning.

$$(\delta p\ \text{RMS})^2 = 1/2(\delta p\ \text{max})^2$$

then

$$\text{Output} \quad = \frac{4\pi r^2 (\delta p \text{RMS})^2}{\rho c}$$

If the above terms are expressed in CGS units, the output is obtained in ergs/sec. This gives an inconveniently large number, and it is usual to convert it to watts by dividing by 10^7. Most of the intensity measurements were made at a distance of 20 ft from the whistle.

Variation of Output with Diameter of Tube

The output of a number of whistles made by pressing the same composition into a series of steel tubes of different diameters was measured. The tubes were all four inches long and the composition was pressed to within 1.5 inches of the open end of the tube. The results are given in Table 1 and plotted in Figure 6. The composition used consisted of 30 parts of potassium benzoate and 70 parts of potassium perchlorate. From elementary reasoning it might be considered that the output would be proportional to the square of the diameter of the tube (i.e., the surface area of the burning composition) or, what is the same thing, the amount of composition consumed per second. In actual fact it will be seen that over the range of tube diameters investigated it varies approximately as the cube of the diameter.

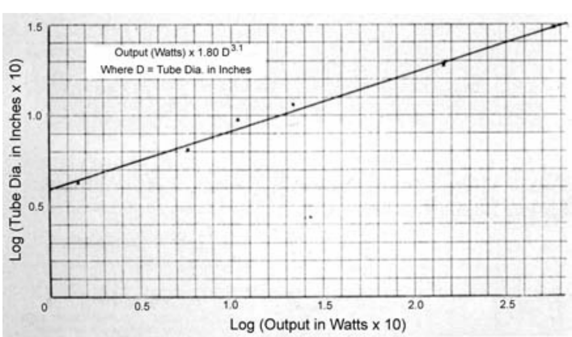

Figure 6. Effect of tube diameter on acoustic output.

Table 1.

Tube Diameter *in.*	Wall Thickness *in.*	RMS Pressure at 20 ft *dynes/sq cm*	Output *watts*
3.01	0.08 – 0.09	72.0	57.6
1.9	0.048	36.3	14.6
1.16	0.048	14.0	2.18
0.94	0.03	10.0	1.11
0.64	0.03	7.3	0.592
0.34	0.03	3.59	0.143

The composition used in the above experiments was found to whistle in steel tubes of as low a diameter as 0.2 inches.

Quality of the Sound from Tubes of Different Diameter

The notes obtained from whistles of diameter not greatly exceeding one inch were in general very pure and the wave-forms obtained from the oscillograph record or direct observation on a cathode ray tube with synchronised time base were sinusoidal. An exception was furnished by a composition containing 70 parts of potassium 2:4 dinitrophenate and 30 parts of potassium nitrate which in a “coachman’s lamp” type of tube 0.93 inch in diameter gave a peculiar wave-form with alternate high and low peaks (frequency 2380). The notes obtained from larger whistles of diameter approximately three inches were very raucous and the waveform was no longer purely sinusoidal but very irregular in shape.

Effect of Material of Tube on Output

Several different materials including aluminum and bakelised paper were used for the tubes, but they made little difference to the output.

Variation of Output with Proportion of Ingredients

A series of compositions containing different proportions of potassium benzoate and potassium perchlorate were burned in a coachman's lamp type of whistle with a constant length of resonating tube and the output measured. The results are plotted in Figure 7 together with a rate of burning curve. It will be seen that the proportions of ingredients for the maximum output are quite critical. The maximum output does not correspond to the maximum rate of burning, but the proportions of the ingredients are quite close to those required for complete combustion.

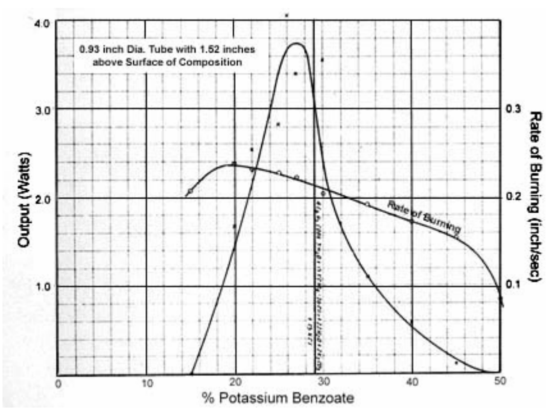

Figure 7. Effect of proportion of ingredients of acoustic output. [Ed. Note: The text on the line at about 29% Potassium Benzoate is $4\ C_6H_5COOK{\cdot}3H_2O + 15\ KClO_4 \rightarrow 26\ CO_2 + 22\ H_2O + 2\ K_2CO_3 + 15\ KCl$.*]*

Photography of Flames of Pyrotechnic Whistles

A photograph of a pyrotechnic whistle taken in a rotating mirror of the Wheatstone type is shown in Figure 8. The intermittent nature of the flame is clearly visible. A sequence of direct photographs of a pyrotechnic whistle taken on a special form of high speed camera is shown in Figure 9. In order to increase the light output from the flame so that a good image could be obtained with very short exposure time, the potassium benzoate/potassium perchlorate mixture was modified slightly by the inclusion of 5 per-

Figure 8. Photograph of pyrotechnic whistle in rotating mirror.

cent of fine magnesium powder. The composition was pressed to a depth of two inches in a steel tube about 1 inch in diameter and 8 inches long. The whistling frequency was about 1000 cycles/sec and the photographs were taken at about 1500 frames a second with an exposure time of approximately 1/25000 sec. In order to try to get some information on the movement of the flame inside the tube, a narrow longitudinal slot 0.03 inch wide was cut in the wall of a whistle of the above type from the top of the tube almost to the surface of the composition and the burning whistle photographed on a drum camera. A portion of the record is shown in Figure 10. It is clear from this that the intermittent flame starts at or very near to the surface of the composition.

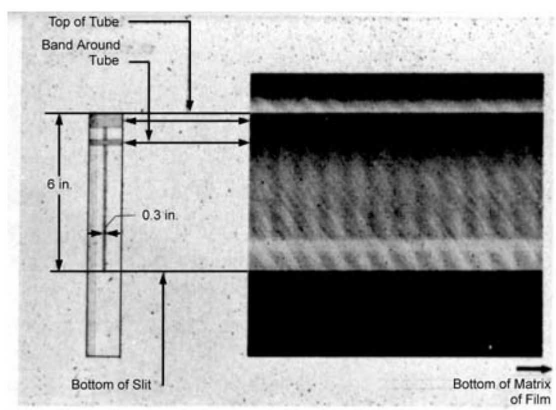

Figure 10. Drum camera photograph of a whistle with a slit in tube.

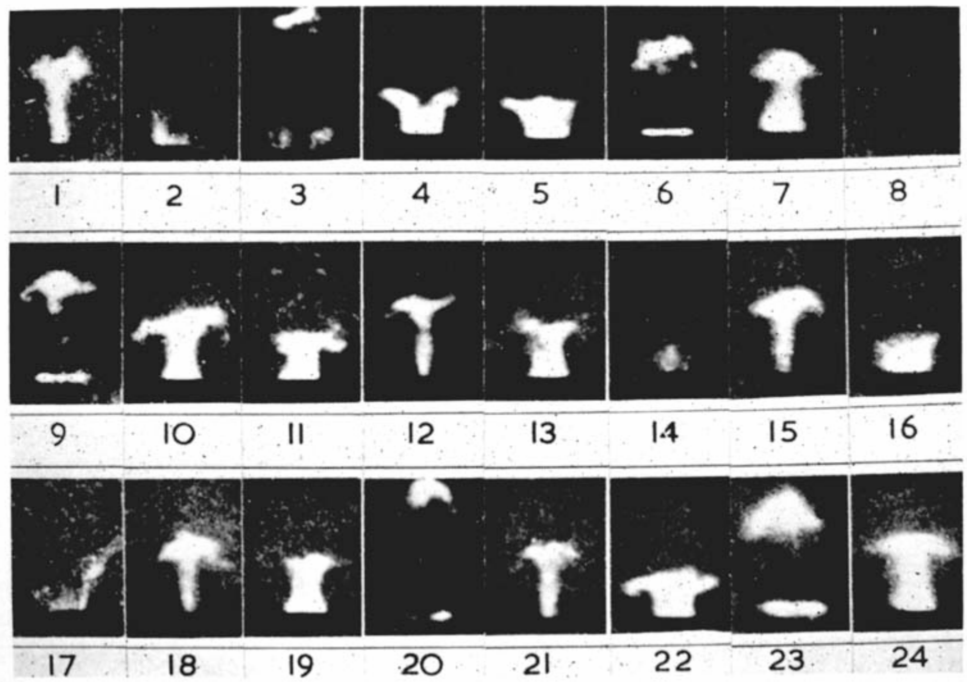

Figure 9. High speed photographs of flame of pyrotechnic whistle.

Effect of Crystal Size of Ingredients

The general effect of crystal size was not investigated. The compositions consisting of potassium perchlorate 70 parts / potassium benzoate 30 parts and also potassium dinitrophenate 70 parts / potassium nitrate 30 parts were found to whistle either much more faintly or not at all if either of the ingredients were only coarsely ground. One series of experiments with the latter composition gave the following results [See Table 2]. The batches of composition were pressed in half-inch diameter steel tubes under a dead load of two tons. The length of the column of composition was about 1.5 inches and the initial depth of the burning surface from the top of the tube about 1.25 inches.

Table 2. Effect of Crystal Size.

	Potassium Dinitrophenate Particle Size	Potassium Nitrate Particle Size	Reciprocal Rate of Burning	Whistling Properties
A	Passing a No. 120 BS sieve	Passing a No. 120 BS sieve	3.0 sec/in	Composition whistled strongly
B	Passing a No. 25 BS, retained on a No. 40 BS sieve	Passing a no. 120 BS sieve	3.0 sec/in	Composition whistled somewhat less intensely than A
C	Passing a No. 120 BS sieve	Passing a No. 25 BS, retained on a No. 40 BS sieve	3.5 sec/in	Low intensity whistle
D	Passing a No. 25 BS, retained on a No. 40 BS sieve	Passing a No. 25 BS, retained on a No. 40 BS sieve	4.3 sec/in	Very low intensity whistle, just faintly audible

The Effect of Lowering the Pressure on the Rate of Burning of Pyrotechnic Whistles

The effect of reducing the atmospheric pressure on the burning of pyrotechnic whistles filled potassium perchlorate 70 parts, potassium benzoate 30 parts, was examined down to a pressure of 10 inches of mercury. The compositions continued to whistle down to this pressure and the rate of burning decreased as shown in Figure 11 where the reciprocal of the rate of burning is plotted against the pressure.

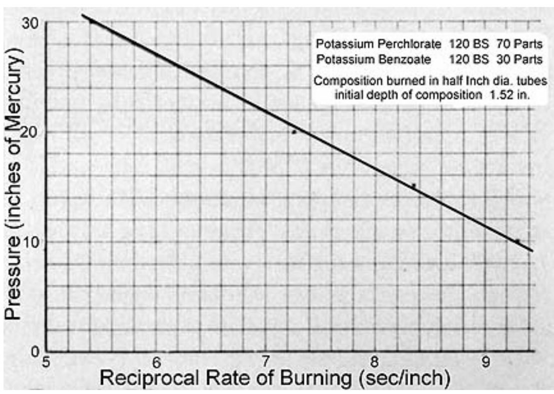

Figure 11. Effect of pressure on the rate of burning of a whistling composition.

Effect of Spin on Whistling Compositions

It is a well known fact that many pyrotechnic compositions when spun about on axis perpendicular to the plane of the burning surface, burn considerably more rapidly. The effect can be explained as due to an increase in burning area resulting from the action of centrifugal force on molten reactants in the burning surface. Compositions which burn with a solid surface do not show the effect. A number of shell tracer bodies consisting essentially of a thick walled tube of 0.375 inch internal diameter were filled with the potassium perchlorate / potassium benzoate composition and spun about their longitudinal axis in an electric spinning machine at speeds up to 30,000 rpm. The spin had no appreciable effect on the rate of burning and the composition whistled normally at all speeds of rotation. It can therefore, be concluded that the burning surface is solid.

The Mechanism of Burning of Pyrotechnic Whistles

It can be inferred and it has been proved above that a whistling composition burns intermittently. Every time the surface is ignited a wave of condensation passes down the tube and is reflected as a wave of rarefaction from the open end. This wave of rarefaction strikes the surface of the composition where it is reflected without change of phase back to the mouth of the tube. At the mouth of the tube it is reflected with change of phase, i.e., as a wave of condensation and travels down to the surface of the composition. It is evident that it is these waves of condensation and rarefaction which cause the composition to burn intermittently, but the exact mechanism is not clear. The variation in pressure which they produced on the surface of the composition are quite small (usually a few ounces per square inch and at the most one or two pounds per square inch) and cannot account for the violent fluctuations in the rate of burning by the simple effect of pressure on rate of burning which is normally observed with propellants and other compositions, since the rate of burning of whistling compositions is not abnormally sensitive to pressure. Now, as already mentioned, the fact that spin has no significant effect on the rate of burning of whistling compositions suggests that they burn with a solid surface. This is confirmed by the almost complete lack of solid residue in the tube of a burnt out whistle. Further, whistling compositions are porous since they consist of consolidated crystals. There would thus appear to be some connections between whistling power and the presence of a solid porous[1] burning surface com-

[1] Wax would be expected to destroy the porosity of the surface and thus reduce the power to whistle. A small proportion of wax in the composition does in fact have the effect of reducing the power to whistle — the greater the proportion of wax the lower the frequency at which whistling commences. Unfortunately wax also has the normal effect of reducing the rate of burning, and slow burning compositions only whistle at low frequencies. It is difficult to separate the two effects.

posed of fine crystals. (It will be recalled that compositions containing only coarse crystals do not whistle satisfactorily.) All whistling compositions known to the author contain a chlorate, a perchlorate or the salt of an organic acid, and small crystals of one or other of the ingredients will be found to decrepitate in a flame. On the basis of these facts it is suggested that the mechanism of combustion of pyrotechnic whistles is roughly as follows. The combustion of a whistling composition whether in a tube or in the form of a pellet involves the explosion of crystals as an essential part of the process. If the composition is not contained in a suitable tube, these crystals will explode in a random fashion and the products of combustion will flow from the surface at a uniform rate and no definite note or indeed any sound of appreciable intensity will result. If, however, the composition is contained in a suitable resonating tube, the flame will be forced in and out of the surface by alternate waves of compression and rarefaction and every time it is forced into the surface a fresh mass of crystals will explode.

Reaction of Pyrotechnic Whistles

It had been observed in the course of the work described in the present paper that pyrotechnic whistles pressed in light tubes tended to wander about if knocked over on their side and to possess a reaction greater than would be obtained from an ordinary pyrotechnic composition burning at a comparable speed. Accordingly some measurements were made on the reaction of such whistles. The apparatus employed consisted of a small condenser gauge dynamometer used in conjunction with a cathode ray oscillograph and a drum camera. The whistles were fired vertically and since the reaction must alternate between positive and negative and the instrument could not record the negative reaction, it was necessary to weight the whistle so that the total downward force was always positive. As would be expected the mean resultant reaction is positive and can be measured by putting a suitable low pass filter into the electrical recording circuit. It was found that this resultant reaction first increased directly with the length of the resonating tube, or inversely with the frequency, and then became steady. The potassium perchlorate / potassium benzoate mixture pressed in a steel tube, 1.9 inches in diameter gave a resultant reaction of about 6.4 oz for a tube length of 1.5 inches and 20.2 oz for a tube length of approximately 3.5 inches. There appeared to be no significant increase in thrust with a tube length of 5.5 inches. A similar tube filled with gun powder meal gave an almost steady reaction of 4.0 oz. The reaction for the gunpowder calculated from the momentum of the products, which can be deduced approximately from chemical and thermal data, was 3.6 oz so that agreement between theory and practice is quite good. The corresponding reaction for the potassium chlorate/potassium benzoate composition burning smoothly (i.e., without whistling) at the same rate as when whistling was calculated to be 3.8 oz which is considerably less than that observed. The detailed explanation of the reaction is not simple. It is known that a resonator exposed to a source of sound gives a resultant thrust but this explanation is inadequate in the present case.[1]

Most of the thrust probably arises from a somewhat similar mechanism to that in the impulse jet motor as fitted, for example, to the German VI, except that combustion is independent of a supply of atmospheric air. The rapidity with which the composition burns at each impulse causes the pressure inside the tube to build up above atmospheric, owing to the inertia of the gases above the composition; the subsequent expansion of the combustion products results in their having a greater momentum than in smooth combustion. After each impulse the pressure inside the tube will fall below atmospheric and result in a negative reaction. The theory of reaction due to a pulsating gas stream is of interest in a negative reaction. The theory of reaction due to a pulsating gas stream is of interest in connection with the back pressure in the exhaust pipes of internal combustion engines and has been investigated to some extent from this point of view.[2]

The Burning of Pyrotechnic Whistles under Water

This aspect of the work on pyrotechnic whistles will only be mentioned briefly. It was soon established that several pyrotechnic compositions when pressed in open tubes of the same type as those used in experiments in air, would burn under water. When a whistle burns under water, it can be distinctly heard above the surface, although the intensity is greatly reduced: (a) The low transmission coefficient between gas and water; (b) The low transmission coefficient between water and air. The sound is also changed in quality for it is intermittent and very much like the chirping of a canary. The most probable explanation of this is that before the tube of the whistle can behave as an open ended pipe, there must be a certain volume of gas surrounding the open end. But the gaseous products of combustion escape in a series of bubbles so that the end conditions vary continuously and are frequently not satisfactory for resonance. The problems of getting the best end conditions formed part of the wider problem of getting the maximum amount of sound energy with the correct frequency distribution into the water, but this will not be dealt with here.

References

1) J.W.S. Rayleigh, *Theory of Sound*, Vol. 2, Dover, 1945, p 42.

2) H. Martin, *Auto-Technische Zeit*, Vol. 10, 1935, p 243.