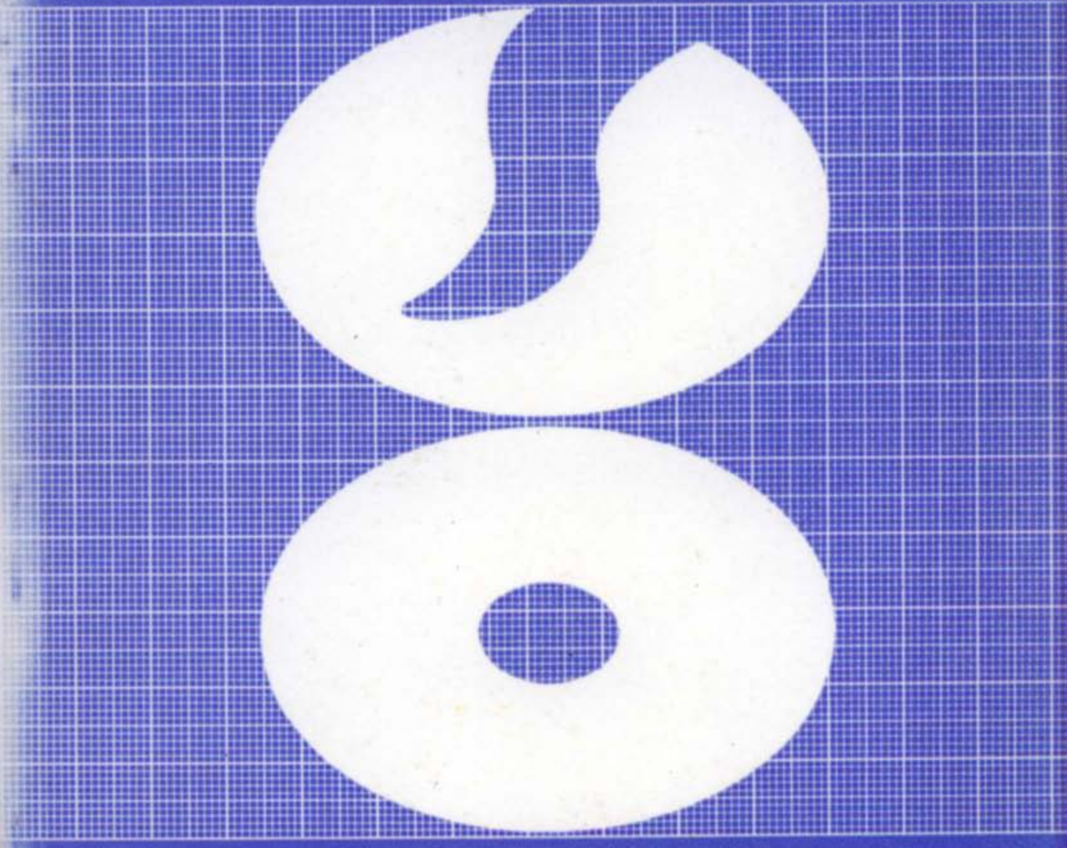
The Air Gun from Trigger



to Muzzle

by G.V. Cardew, G.M. Cardew, and E.R. Elsom

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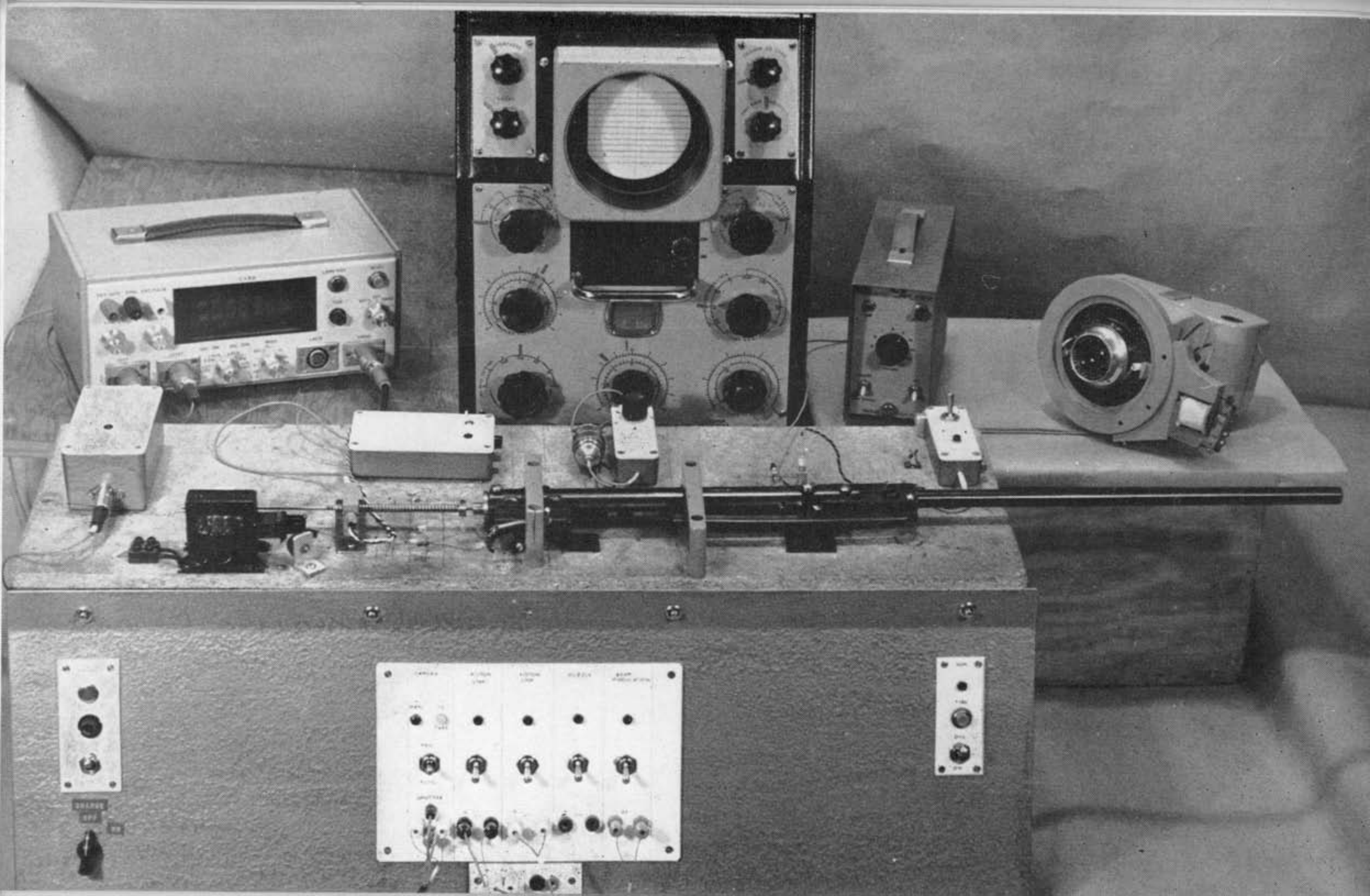


FOREWORD

This book is the culmination of five years work by three people; it concerns only the internal ballistics of spring operated air weapons. That is, what happens inside the rifle during the brief time between the trigger being pulled and the pellet leaving the muzzle. It is in fact all about a period of time which only amounts to fifteen thousandths of a second. Once out of the barrel the pellet becomes subject to the laws of external ballistics which are outside the scope of this present work.

In the past there have been many attempts to explain how and why an air weapon works, but in the main these have been based upon "hit and myth" without much experimental investigation to back them up; for instance, it has long been believed that the longer the barrel of an air weapon the higher the velocity is going to be. We have proved that this statement is untrue.

Our experiments have been mostly based on a weapon mounted on a test bed (Fig. 0.1). This weapon was of standard barrel cocking design and represented many makes. We have tried to investigate each component and action separately and accurately so that we could arrive at a reasonable conclusion that accounts for all the energy stored in the spring. At the same time, however, all this was done on a very limited budget by three enthusiastics working only in their spare time. We often had to rely on other people for the loan of sophisticated equipment, or as in most cases, home made equipment.

We in no way offer any huge improvement in the power of your rifle, but we do set out to give you a far better understanding of the processes that go on inside your air rifle when you pull the trigger.

We might point out at this stage that none of the authors have any connection with an air rifle manufacturer, nor, at the time of writing, have we been into an air rifle factory. This has been partly a matter of policy so that we could maintain complete independence of thought on the subject and no conflict of interests could arise.

Although this work is solely about spring operated air weapons, many of the facts mentioned apply equally well to pneumatic and gas operated weapons.

Illustration opposite
0.1 The test bed

ACKNOWLEDGEMENTS

We are greatly indebted to Messrs. Kistler Instruments for the loan of expensive pressure measuring equipment. Also to Mr. C. B. Daish and the staff of the Royal Military College of Science, Shrivenham; who helped us with advice and encouragement from the start.

Our thanks to our great friend, Mr. L. Wesley, for if it were not for his book, "Air Guns and Air Pistols" this book might never have been written. We also thank Mr. A. Terman and Mr. R. Jeffery for their contributions to the chapter concerning chronographs.

Finally, we wish to express our gratitude to Mr. John Watts, author of "The Bayonet Book", who helped us out in one or two sticky moments!

CHAPTER ONE
INTRODUCTION AND SEQUENCE

It is a surprising thing that very often a subject that appears on first sight to be so simple, often, on further study, turns out to be very complicated. This statement is exceptionally true when applied to the spring air weapon, as we found out when we first began to investigate the subject some five years ago.

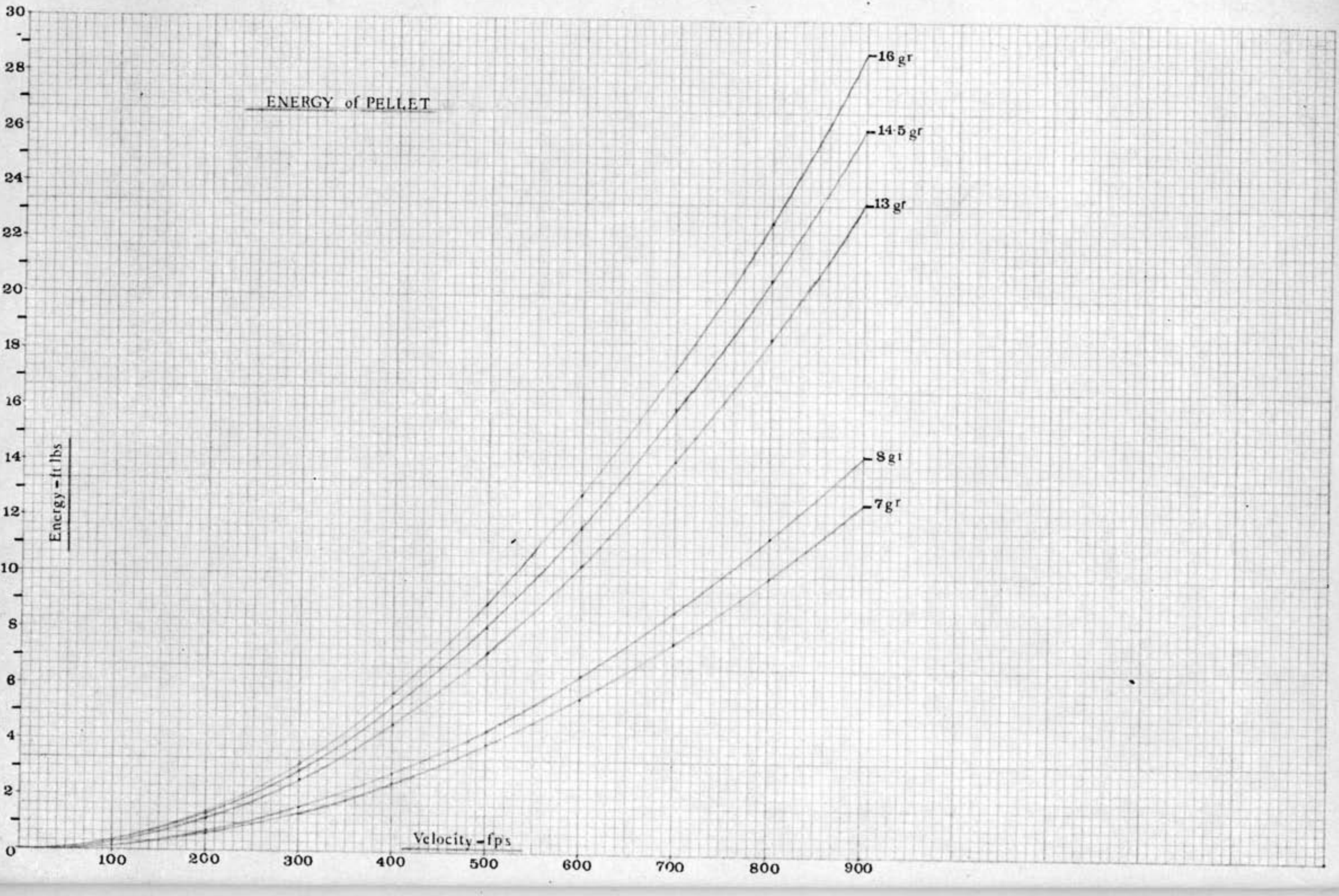
The trouble all started with a small barrel cocker that we bought secondhand. Generally it would perform very well and give successively accurate shots, then for no apparent reason the pellets would go high or low causing much frustration. Being scientifically minded and curious we decided to try to improve on the original construction by making the breech seal a better fit. Then the cylinder was polished and the sear refitted. Each alteration and adjustment helped but the real reasons behind the problems still remained obscure.

More rifles were looked at and some bought so that we could examine them and check their performance. In each case we measured, what we considered, at the time, to be the "vital dimensions", as, by this procedure we hoped that we should be able to spot why one type of rifle was better than another. But it soon became clear that physical dimensions alone were not going to be the answer, there must be other areas to be investigated.

We were not able to accurately compare one gun with another since we had no means of measuring velocity. This was a big problem that held up our investigations from progressing beyond elementary stages. We then thought of the age old instrument called a Ballistic Pendulum which had been in use years ago for the study of the ballistics of musket balls. This device offered such a cheap and simple answer to our problems that we immediately set about developing a variation of the instrument that would be suitable for use with air rifle pellets. However, we soon grew out of this, and found that although we could measure velocity accurately with the pendulum, when many readings had to be taken in quick succession a chronograph was required. A halt had to be called to gun investigations whilst we built an electronic chronograph. This turned out to be capricious, having a mind of its own on many occasions, but it proved to us that a chronograph could be built to a high standard of accuracy without spending a fortune. We were then lucky enough to find an electronic specialist who built a tailor made instrument to meet our own special requirements, but more about it and other chronos. in another chapter.

By this time we were utterly and completely committed to the solution of the problems of air guns and why so little of the energy in the spring appears in the pellet as it leaves the muzzle. We hope that in the following chapters, the reader will find the answer to his own particular questions and will be better able to understand the physics that are involved in his gun.

Perhaps the most fundamental question that must be asked is, why use air at all? After all, a bow projects an arrow without air and also a catapult can


ENERGY of PELLET
Energy - ft lbs
Velocity - fps
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
100
200
300
400
500
600
700
800
900
16 gr
14·5 gr
13 gr
8 gr
7 gr

fire a stone. So perhaps the air makes it all work better and more efficiently, or gives it more energy? Well, no. The air is only a medium used to couple the heavy, relatively slow moving piston to the light fast moving pellet. It is this great difference between the weight of the driving force and the projectile that makes a coupling medium necessary. This will be discussed more fully in a later chapter on the air including what happens when gases other than air are employed.

Physics is a subject full of graphs, so the reader must accept them as a necessity in a book of this nature. The first one that we shall use (fig. 1.1) relates three factors, pellet weight, pellet velocity and pellet energy. One of the chief uses of this diagram is to compare two rifles of different calibre, but it can also be used to compare pellets of different weights fired from the same rifle. It makes these comparisons possible by providing the means of converting weights and velocities to that all important figure, the muzzle energy.

Over the years, manufacturers and sportsmen have always spoken of, and perhaps boasted about, the velocity of their favourite rifle. Whilst this may be quite reasonable in advertisements or in the bar of the "Red Lion" it has little place in physics, for no mention has been made of the weight of the projectile. It is rather like telling your friends that you can travel at 50 miles per hour. This is not remarkable at all, until you carry on to mention that you do so by bicycle or steam roller. Weight is just as important as speed, a fact that is easily overlooked.

In order to determine the energy of any projectile, it must first be weighed and then the velocity at which it is travelling measured. These two facts provide all the information that is required. Normally the speed reading is taken within six feet or so of the muzzle, at this point the projectile is at its maximum velocity and the blast from the gun has minimum effect on the measuring instruments.

These two factors, weight and velocity, can then be substituted in Newton's well known equation for kinetic energy.

$$E = \tfrac{1}{2}MV^2$$

Where E = Energy, M = Mass, V = Velocity

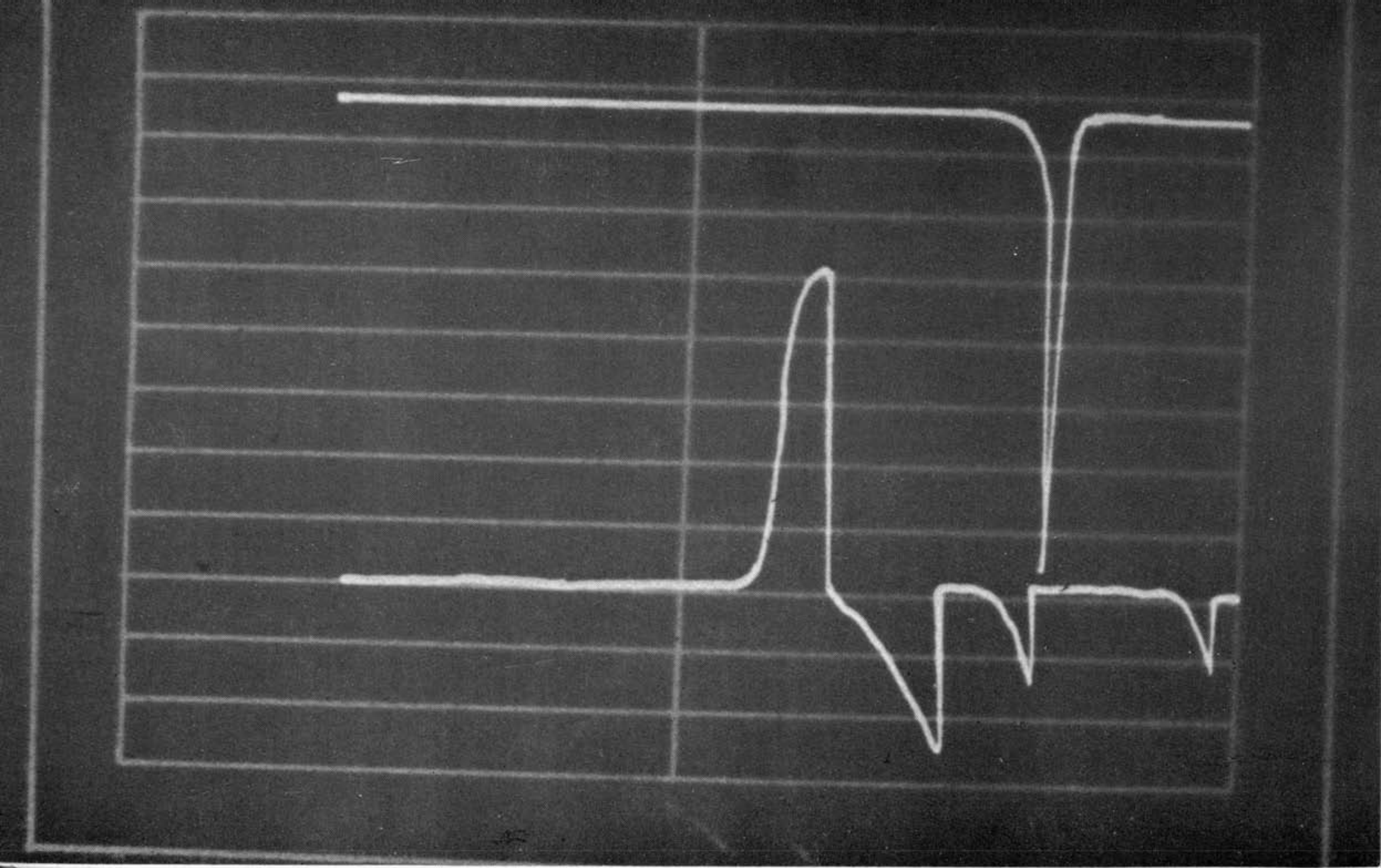
But since we are dealing here with weight and not mass we must convert the equation into:

$$E = \tfrac{1}{2}\,\frac{WV^2}{g}$$

Where W = Weight and g = the acceleration due to gravity. Which in this book will be taken as 32.16 ft./sec.

Illustration opposite

1.1. Pellet Energy graph



This will give us the kinetic energy which that projectile contains when it travels at velocity V.

Suppose that we wish to determine the energy of a pellet weighing 14.5 grains that is travelling at a velocity of 500 FPS.

We must first apply the abive formula where; $W = 14.5$ Grains, $V = 500$FPS $g = 32.16$ FPS^2. To convert grains to pounds we have to divide by 7000.

So:

$$E = \frac{14.5 \times (500)^2}{2 \times 32.16 \times 7000}$$

$$E = \frac{3625000}{450240}$$

$$E = 8.05 \text{ Foot Pounds}$$

(One foot pound being the amount of energy required to raise one pound through one foot).

We have found throughout our work with air weapons that the overall mechanical efficiency of an average air rifle is about 30%. That is for every foot pound of energy contained in the compressed spring only 1/3 of a foot pound appears as energy in the flying pellet. The reasons for this inefficiency have been investigated and appear, each in turn, in the following chapters. However, in order to start understanding the working of an air rifle, one must know the sequence of the events inside the gun, for instance, does the pellet start at the moment of peak air pressure? Does this piston stop before the pellet leaves the barrel? etc.

The time sequence was established by making the various moving components of the gun such as the piston and pellet interrupt light beams which in turn produced electrical pulses that were displayed on an oscilloscope trace (fig. 1.2). The piston starting, the piston stopping, the pellet starting and the pellet leaving the end of an eighteen inch barrel each produced a pulse on the top trace of the oscillogram. The only negative pulse (downward going) on the trace is that of the piston stopping. The bottom trace shows the pressure rise inside the cylinder as measured in this instance with an uncalibrated transducer.

Illustration opposite
1.2 Time sequence

The first positive pulse is that from the piston starting after the trigger is pulled, the second is that from the pellet as it starts off up the barrel, the third positive pulse therefore must be that of the pellet leaving the muzzle of the gun and the fourth (and only negative) pulse is that of the piston finally stopping at the end of the cylinder.

So summarising the above sequence; the piston starts, the pellet then starts, (notice that this happens at the point of peak pressure), the pellet then leaves the barrel and the piston comes to rest at the end of the cylinder soon after. It will be shown in a later chapter that in fact, the piston comes very close to the end of the cylinder at the moment of peak pressure, but then rebounds backwards off the high pressure air in front of itself.

It must be borne in mind throughout this book that everything happens at very high speed. For instance, the time base of the oscillogram, i.e. the length of the horizontal line is equivalent to 50 milliseconds, that is, fifty thousandths of a second ! ! Thus the total time from the start to the stop of the piston is about 1/3 of 50 m.s. This is shown by the fact that the cycle of events is completed in the first third of the length of the trace in Fig. 1.2. In this time a pellet travelling at 500 feet per second would have covered a distance of eight feet ! !

CHAPTER TWO
THE SPRING

The spring of an air rifle is basically only a reservoir employed to store the propelling energy during the brief period between cocking and firing the weapon. In order to obtain an indication of the efficiency of an air rifle, it is necessary to determine the amount of energy actually contained by the spring when it is compressed, the energy being measured in foot pounds.

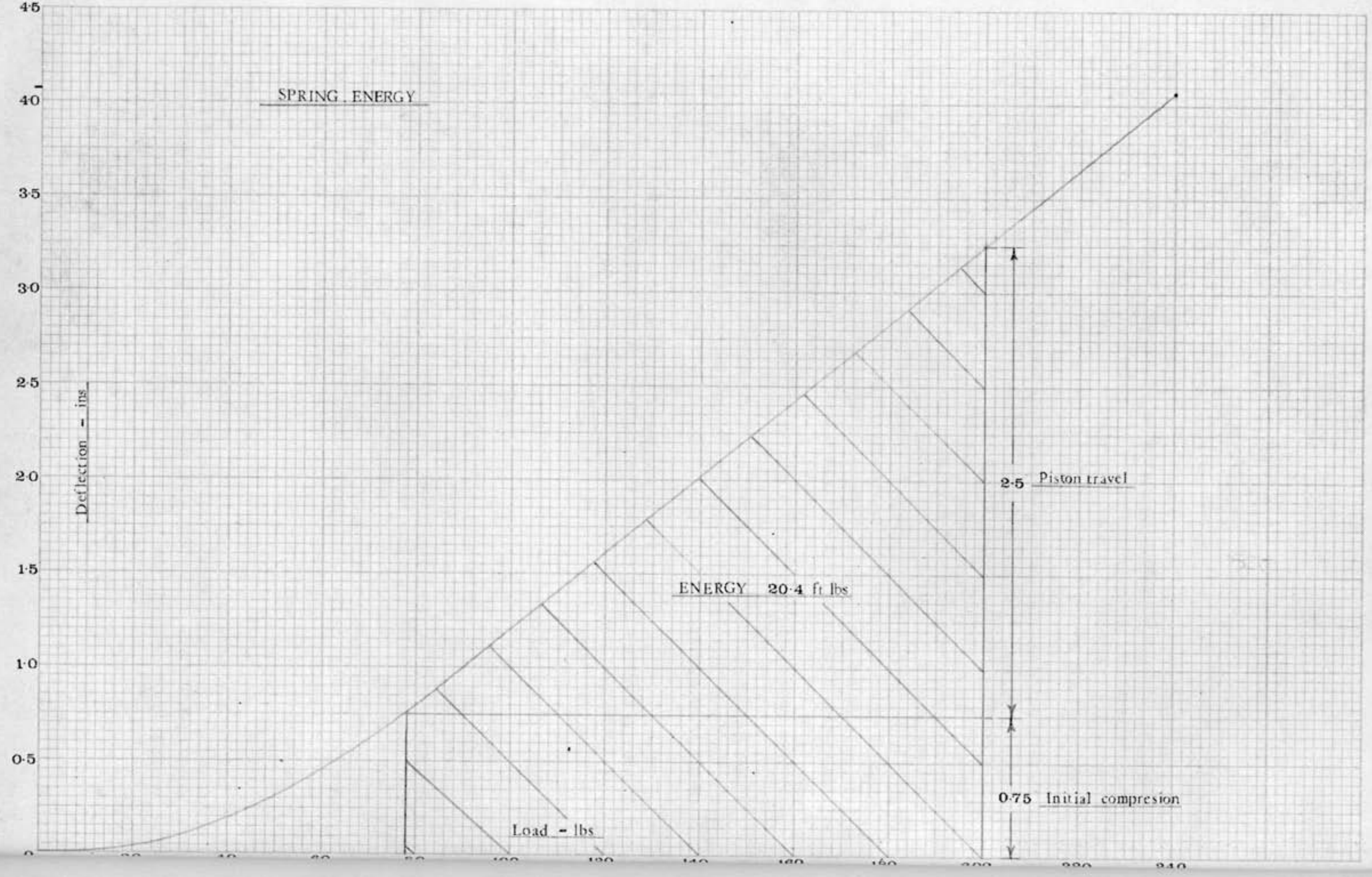
It is, unfortunately, a rather tedious undertaking to establish this amount of energy accurately, however a crude, but effective method of determination is well worth description. Energy is the capacity a body has for performing work. Hence, if we can determine the amount of work done on the spring as the gun is cocked, and assuming that the spring stores all this energy, which it does, then the work done on the spring equals the energy stored by it. Now the work done is the product of the average force applied when cocking and the distance through which it is applied. In this instance the average force may be taken as the force applied to the cocking lever when it is mid-way through its travel. This can be measured with a spring balance.

The above method is rather crude since it takes no account of the frictional losses at the pivots or piston during the cocking stroke. On the test weapon, which was cocked by means of the barrel, the muzzle end of the barrel travelled a distance of 22 inches during cocking (having taken up the initial lost movement of the lever system).

It must be noted that this is not a straight line measurement, but an arc. The force that had to be applied to the muzzle at the half way point of the arc was ten pounds, thus the work done on the spring, and hence the energy contained by it was 22 x 10 inch pounds or (dividing by 12): 18 ft. lbs. This figure is in fact only 2.4 ft. lbs. different from the actual value of 20.4 ft. lbs., but is perfectly acceptable considering the method used to obtain it.

A more accurate method than the above is achieved by removing the spring from the gun and establishing its load/deflection curve. This line (drawn for our test weapon in Fig. 2.1), represents the amount by which the spring is deflected for a given load, if the load is in pounds and the deflection in inches, then the area beneath the line represents the number of inch pounds contained by the spring. These units of energy may be converted into the more usual foot pounds by simply dividing by 12. The total area under the line is therefore a representation of the maximum amount of energy that can be put into that particular spring. This amount of energy is limited at the point the coils touch one another, or become "coilbound".

The amount of useable energy contained within a spring when the gun is cocked can be determined by taking the area under the curve only between the limits of initial compression and the fully cocked compression, i.e. the piston travel. Initial compression being the amount by which the spring is compressed when it is uncocked in the gun. The piston travel is, of course, the distance


SPRING ENERGY
4·5
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
Deflection - ins
ENERGY 20·4 ft lbs
2·5 Piston travel
0·75 Initial compresion
Load - lbs

covered by the piston from the moment of release to the front end of the cylinder.

In order to draw this line accurately, the deflection for a given load must be determined. To do this, the spring could be placed upright on a solid bench. A bar is then passed through the centre of the spring and also through the bench. The bar is prevented from passing right through the spring by a nut and washer or some other such fastening at the upper end of the rod. A lightweight tray should then be placed on the lower end of the rod and weights placed on it in increments of about ten pounds. The initial length of the spring should be measured with a rule and then successive readings made as weights are applied, and again as they are removed.

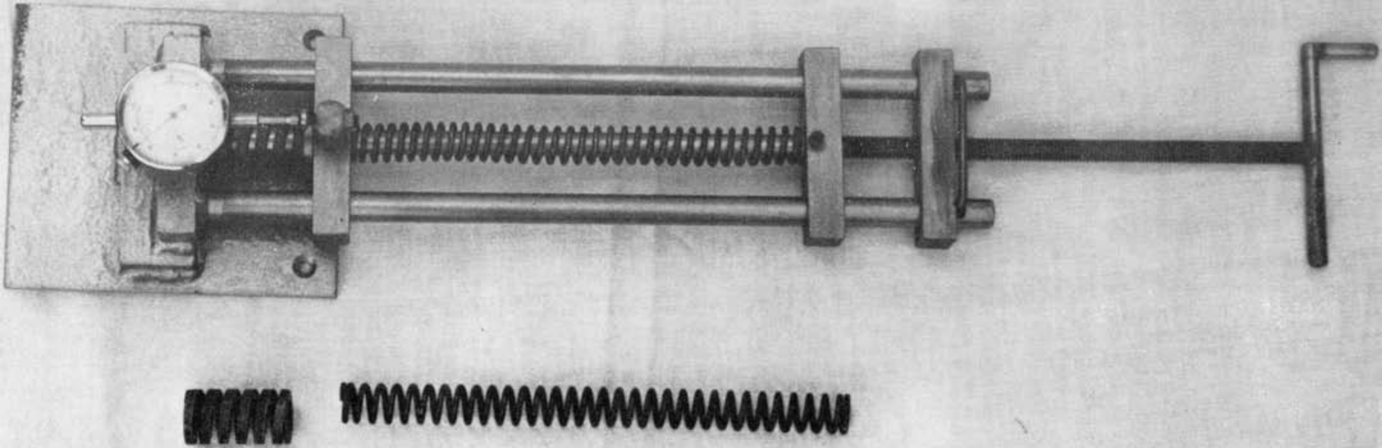
This procedure should be repeated to obtain two sets of results, the average of which are taken and plotted on a graph (as Fig. 2.1.). It will be noticed that this line is not straight, but curves slightly for the first 70 or 80 pounds. This is unfortunate, since if it were straight, only one point need be plotted, a line could then be drawn through it and the origin and the graph would be complete.

The initial compression is conveniently determined when the spring is being replaced, this and the piston travel are then drawn on the graph and the area between these two limits found. For simplicity, the area may be taken as that of a trapezium, which may be calculated by multiplying half the sum of the parallel sides by the distance between them. The result given is the total energy expressed in inch pounds.

It was, however, necessary for us to determine the energy storage capacity of a number of springs. We therefore built a piece of apparatus (Fig. 2.2.), which enabled us to conveniently test any air weapon spring quickly and accurately. Instead of using weights, as in the previous method, the spring was compressed against an extremely strong spring whose load/deflection curve had previously been accurately dtermined. When the handle was rotated the spring under test was compressed against the tough master spring, the small deflection of this spring was measured by a clock gauge in thousandths of an inch. We knew that for every ten pounds applied to the master spring it deflected 8.5 thousandths of an inch. Thus the handle was turned until successive readings of 8.5 thou. were obtained. At each of these points the length of the spring under test was measured with a rule. The load deflection curve for the spring being investigated could then be drawn, the load axis being plotted in ten pounds intervals.

The initial compression of the spring and the travel of the spring are then established as the gun is re-assembled and these two points are marked on the graph to give the limits between which the area must be determined.

Illustration opposite
2.1 Spring energy graph



In our test weapon, the initial compression was 0.75 ins. (Fig. 2.1), from which it can be seen that the spring has an initial load of 78 pounds. Our piston travel was 2.5 ins. which must be added to the value of the initial compression giving a total sum of 3.25 ins. From the point where the graph line intersects the vertical (deflection) scale at 3.25 ins., a line can be drawn to the horizontal (load) scale, which it meets at the 200 lb. point. The shaded area between these lines and the line of the graph represents the amount of energy contained by the cocked spring. It is interesting to notice that in this case the gun did not make the best use of the spring, if the initial compression had been increased by another 0.8 inch, then when fully cocked, the spring would have been coil-bound and the area under the line would have been greater since the shaded area on the graph would have been shifted to the right. Also, of course, the gun would have been somewhat harder to cock. Alternatively, had the spring been an old one that had lost much of its original length, enough to remove initial compression altogether, then the whole shaded area would have moved to the left, and the spring's energy storing capacity would have been greatly reduced.

This indicates how very important it is to make sure that the spring in an air weapon is as long as the manufacturer originally made it.

Before discussing the materials and manufacturing methods employed in making air weapon springs it is well worth spending some time considering the life that such a spring is expected to lead. It must be capable of being compressed to its limit many times without loss of length. It must be capable of sudden expansion without fracture and resist sideways buckling as far as is possible within the margins of support afforded by the piston. These factors call for a high degree of control by the manufacturer from the selection of the material to the final heat treatment and testing.

When a coil spring is compressed, the energy is, in fact, stored by the wire twisting. If a lightweight compression spring be compressed in one's hands, this will clearly be demonstrated. As each coil closes on its neighbour, the wire in between twists to allow the coils to take up their new position and force is required to overcome the wire's resistance to this twisting. The force necessary to cause a unit compression (the slope of the graph Fig. 2.1.) is a measure of spring "stiffness".

The stiffness of a spring is determined by its physical dimensions according to mathematical laws:—

> If the wire diameter be doubled and everything else remains the same, then the spring will be sixteen times as stiff.

Illustration opposite
2.2 Spring testing machine

> If the diameter of the spring itself is doubled, then the stiffness is reduced to one eighth of its previous value.
>
> If the number of active coils is doubled in a spring of a given length, then the stiffness is halved.

It is quite clear from the above that the design of a spring is a science in itself, many books have been written on the subject and it is well outside the scope of this present work to enlarge on the subject. The air weapon enthusiast wants to be able to assess the properties of a spring by simple rules of thumb where possible. It should be noted that a spring does not lose stiffness ("weaken") during its life, it only becomes shorter.

So, assuming that one removes the spring from a weapon of unknown history, what should one look for when deciding as to its future value as a power unit. A visual inspection will soon reveal whether it has partially collapsed, indicated by the coils being closer together at one place than another. This complaint is usually accompanied by buckling, which is easy to spot, since the spring will be visibly bent. Each of these conditions reduce the performance of the spring by robbing it of its original length which, as we have already shown, is the important factor when evaluating a spring. It is sometimes difficult to determine whether the spring that has been in service for some time has lost some of its original length. If one has a new spring for comparison, then the task is easy, but more often than not, a new one is not available. This being so, the following may serve as a rough guide. Most of the springs that we have met, when new, have a gap of about one and a half times the wire diameter between the coils. Or to put it another way, the spring when fully compressed measures about 0.4 of its original length. Another indication is the amount of initial compression that has to be applied, in most cases this figure is in the region of two inches. It is also advisable to check that the spring is almost coilbound at the cocked position. Thus, using the maximum storage capacity available in the spring. One very often meets up with a weapon that has a spring which is completely unsuitable in this respect.

Whilst on the subject of unsuitable springs, the usual question must be asked: "Can a more powerful spring be fitted?" In most cases the answer to this question is "No". Usually a more powerful spring is too large and the diameter is too great, failing that the length is wrong and the new unit has to be cut down, one then finds that in order to cock the weapon, one has to reduce the length to the point where initial compression is lost. Assuming that a more powerful unit does in fact fit without too much butchering, let us look at the result in terms of muzzle energy. We have already stated that the overall efficiency of a weapon is in the order of only 30%. So for every extra foot pound that the larger spring contains, only 1/3 appears as energy at the muzzle. This small advantage has got to be weighed against the probable disadvantages of increased cocking effort and increased trigger pull.

One Continental manufacturer produces a weapon which is of interest, since the gun contains two springs inside one another. In theory this would seem to be a very good idea, but in practical terms, the results are disappointing since it would seem that the two springs bind together and do not produce the expected power.

It is possible to compare the performance of two springs by their weight. If one were twice as heavy as the other then as a quick rule of thumb, it is reasonable to expect twice the energy storage capacity assuming they are both exploited to their full capacity. This assumes, of course, that the material and temper of both springs are the same.

Most air weapon springs are made from high quality steel wire to B.S. 1429 or B.S. 1408. This is the material that is used for most springs throughout industry. There are, of course, other materials from which springs can be made: Stainless Steel for corrosive applications, or Berilium Copper for non-magnetic applications. We are often asked if there is a better type of steel available which, although more costly, might provide a longer lasting spring that could also store more energy. As we understand it, there are such materials but since they are not normally available, the trouble and expense is not worth the very small advantage to be gained by their employment.

The normal material for springs is manufactured in the form of round wire hardened and tempered ready for winding into the finshed product. It is for this reason that springs of square or rectangular section are not readily available. The high quality steel that is drawn into round wire is, we understand, not drawn into square or rectangular section. So, even if one does get hold of such a spring, the chances are that the advantages to be gained from the larger section will be outweighed by the poorer material.

Once the wire has been wound into a spring, it has only to be stress relieved before it is ready for testing. This stress relieving is carried out at a low temperature over a period of some hours in order to remove the local stresses caused by the winding.

The testing of air weapon springs should consist of compressing them several times until the coils meet, then they should be again compressed solid and left in that state for a number of hours. At the end of that period, they should be released and their length checked to make sure that it is the desired length.

One last point about the air gun spring: at the moment that the gun is fired, the piston and front end of the spring rush forward with such speed that the tail end of the spring is dragged forward also. Now, later on in the book, it will be shown that the piston bounces back off a cushion of compressed air. So at the moment the piston is bouncing the tail of the spring has left its seat at the trigger end of the cylinder. So for an infinitesimal moment of time, the piston and spring are in fact, suspended in the cylinder without the end of either being in contact with anything! Just imagine that when you next pull the trigger ! !

CHAPTER THREE
THE PISTON

The prime function of the piston in any air weapon is to provide an air tight barrier between the spring and the air in the cylinder. It must be able to seal against air leaks between itself and the walls of the cylinder as it moves forward at high speed, yet, at the same time, it must not produce undue friction.

There are only two variables that may be altered in any gun when one is experimenting with the piston to produce greater efficiency. The first is the type of sealing employed, and the second, the overall weight of the piston.

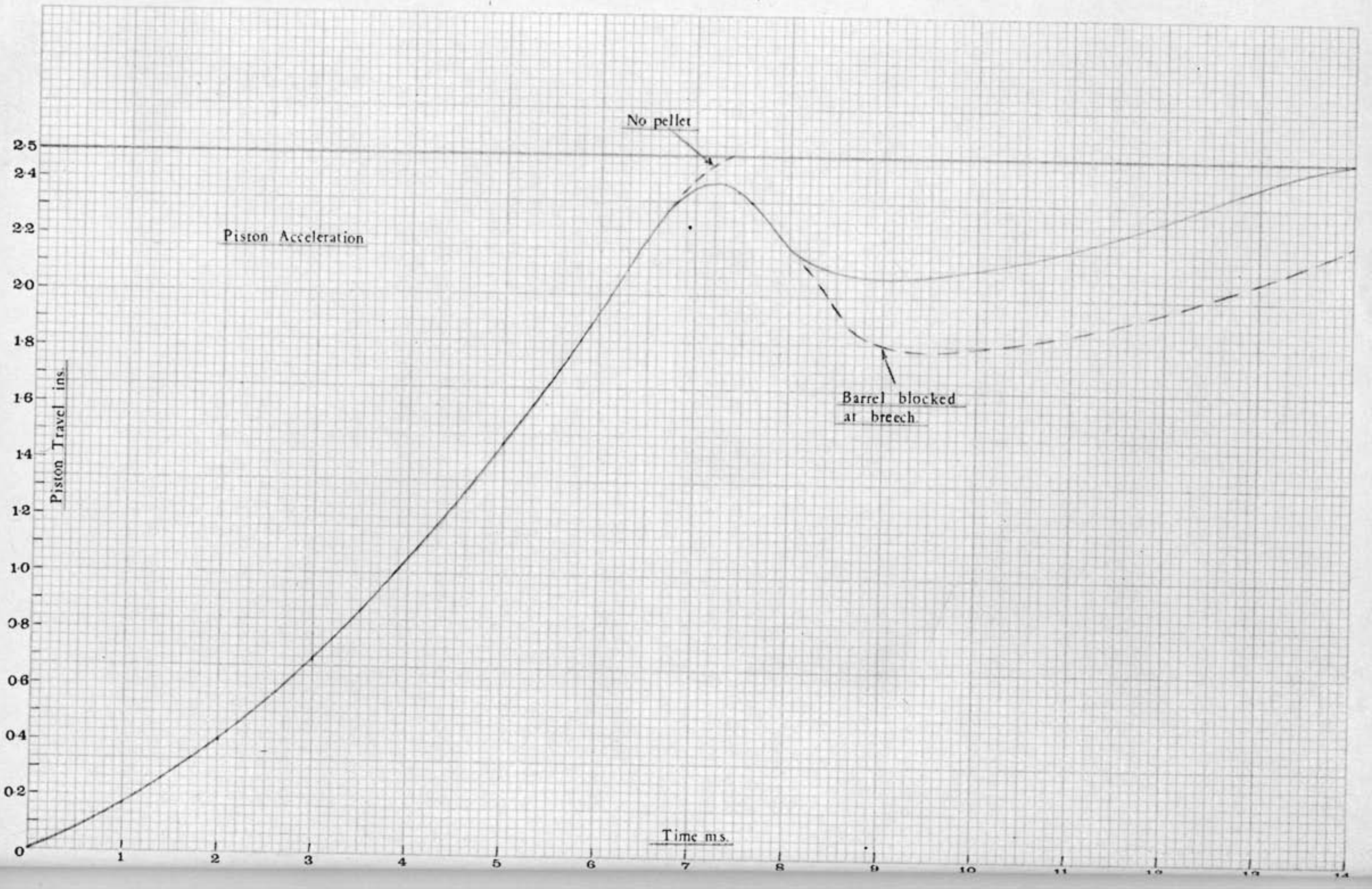
Consider the sealing first; the most common type used throughout the history of spring air weapons is undoubtedly the leather cup washer. Other types are occasionally used, these usually take the form of piston rings made from phosphor bronze, cast iron or a type of plastic moulded to shape.

Our experiments have shown that the sealing qualities are relatively unimportant to the efficiency of the gun. By relative we mean that it is far more important to have a correctly shaped breech than a piston that is completely airtight. Obviously the piston must not let vast quantities of air past, but provided that the clearance is small not much air escapes during the very brief time that the piston is moving. On the other hand, a piston washer that is too tight in the bore produces so much friction that the pellet may not get enough blast to even come out of the barrel.

Seals made from modern plastics such as PTFE (polytetrafluorethylene) are excellent, provided they are in the form of piston rings. Solid washers are liable to be a source of trouble on account of the abnormally high coefficient of thermal expansion of some plastics. In the case of PTFE, the daily change of temperature is enough to change the plastic from a very bad seal into an almost locked solid piston. PTFE, however, is a very versatile material and may be mixed with various substances during manufacture, amongst which molybdenum-disulphide is of greatest interest to us. The result of this mixture is a very slippery self lubricating substance which is ideal for piston rings.

The old fashioned leather washer has stood the test of time and still remains the most popular for all but the most expensive weapons. It has a lot of advantages, besides being amongst the cheapest to produce, it will withstand a lot of abuse in the form of lack of lubrication. We have seen many rifles that have been starved of oil for years, yet when the washer has been cleaned out and re-lubricated it has been as good as new. Another point in favour of leather is that it retains its lubricant like a wick, providing a constant supply of oil to the working surface. Assuming that is, that it has not been soaked with an unsuitable oil in the first place, which will cause dieselling. But more about the problems associated with lubrication in a chapter of its own.

We examined the effect of altering the weight of the piston in some detail. By adding lead weights inside the piston, it was possible to double the original


No pellet
Piston Acceleration
Barrel blocked
at breech
Piston Travel ins.
Time ms.
2·5
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
1
2
3
4
5
6
7
8
9
10

weight. But the results surprised us, since we had expected a large alteration in muzzle velocity, either up or down, we were not sure which. Instead, there was a small reduction in velocity, but the gun immediately become very unpleasant to shoot because of a very pronounced jerk, this jolt is explained in detail in the chapter on recoil. When the piston is heavy, the energy in the spring is transferred more slowly making the gun uncomfortable to shoot. However, a light piston can accelerate faster and hence less jerk is felt. At the other end of the cylinder, a heavy piston is harder to stop than a light one, and although a cushion of air exists between the cylinder end of the washer, the effect of the piston's weight is still very clear.

With these thoughts in mind, it is not difficult to realise that if it were possible to do away with the piston altogether or at least make one out of weightless material, the resulting gun would be exceptionally smooth in action, and would certainly approach the recoilless weapons for competition shooting.

A graph of piston travel against time is shown in Fig. 3.1., (using the standard light piston). It can be seen that the velocity is approximately constant after the initial acceleration, until it nears the end of the cylinder, when it slows down abruptly and stops for an instant at about 1/10 inches away from the cylinder end. From this position it 'bounces' back to a point nearly $\frac{1}{2}$ inch away from the cylinder end, it then returns and comes to rest against the top of the cylinder.

If there were no pellet in the breech that piston would have carried on at the same velocity until it crashed into the end of the cylinder, doing no good to anything! If, on the other hand, the barrel had been completely blocked and no air allowed to escape, then the piston would have bounced back much further than the 1/2 inch. It would then have moved forward again and finally come to rest at the end of the cylinder.

The reason that the piston is forced back, or "bounces", is because at the instant when the piston is at the front of its stroke, the air is at its highest pressure; now the air is not able to transfer its energy instantaneously to the pellet since a pellet requires time to accelerate. Hence the highly compressed air forces the piston backwards until the forward thrust of the spring equals the backward thrust of the air, but, of course, during this backward movement of the piston, the pellet has started off down the barrel, the piston again comes forward, this time completing its stroke.

If, however, it were possible to stop the piston from travelling backwards, this wasteful expansion of the air would be avoided and more energy would be imparted to the pellet. Having realised that this bounce caused such a great

Illustration opposite

3.1 Piston acceleration graph

drop in cylinder pressure, we immediately set about trying to prevent it. We thought up many novel systems and wasted inumerable hours in attempts to hold the piston firmly in the forward position.

It is comparatively easy to accomplish this on a slow speed trial when the piston is allowed to come forward under hand control, but as soon as the gun is fired problems arise. First of all, the piston is at the front of its stroke for an infinitesimal instant of time and secondly, the pressure being exerted upon it at that moment is enormous. Any device capable of restraining it must be able to act instantaneously and must also be strong enough to withstand the backward thrust of the piston, which is the maximum cylinder pressure multiplied by the frontal area of the piston. In our case this resulted in a force of over 1000 lbs. (almost half a ton!).

A sketch of our final attempt is shown in Fig. 3.2. The idea is that the rod can pass freely in the direction of forward piston travel, but as soon as the rod attempts to return, the steel balls lock inside the tapered casing and prevent any further movement. When reloading the weapon, the balls are held away from the casing by the release screw which must be operated at each shot. All the parts of this device were made from tool steel then hardened and polished. Yet, in spite of all our endeavours, upon firing, all the working parts were distorted and the whole unit dragged away from the rear of the gun. At this point we decided that the scheme was impractical since it had become abundantly clear that the forces involved were greater than the average gun could stand. But if a gun could be built that incorporated a non return device, we forsee that the increase in velocity would be significant. It is a great pity that this must remain a debatable point that we have not been able to settle by practical experiment.

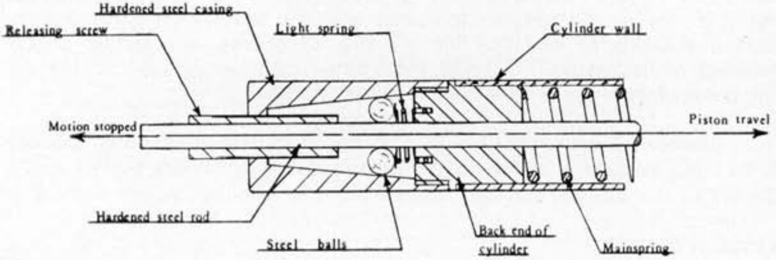


Fig. 3.2. Anti-bounce device

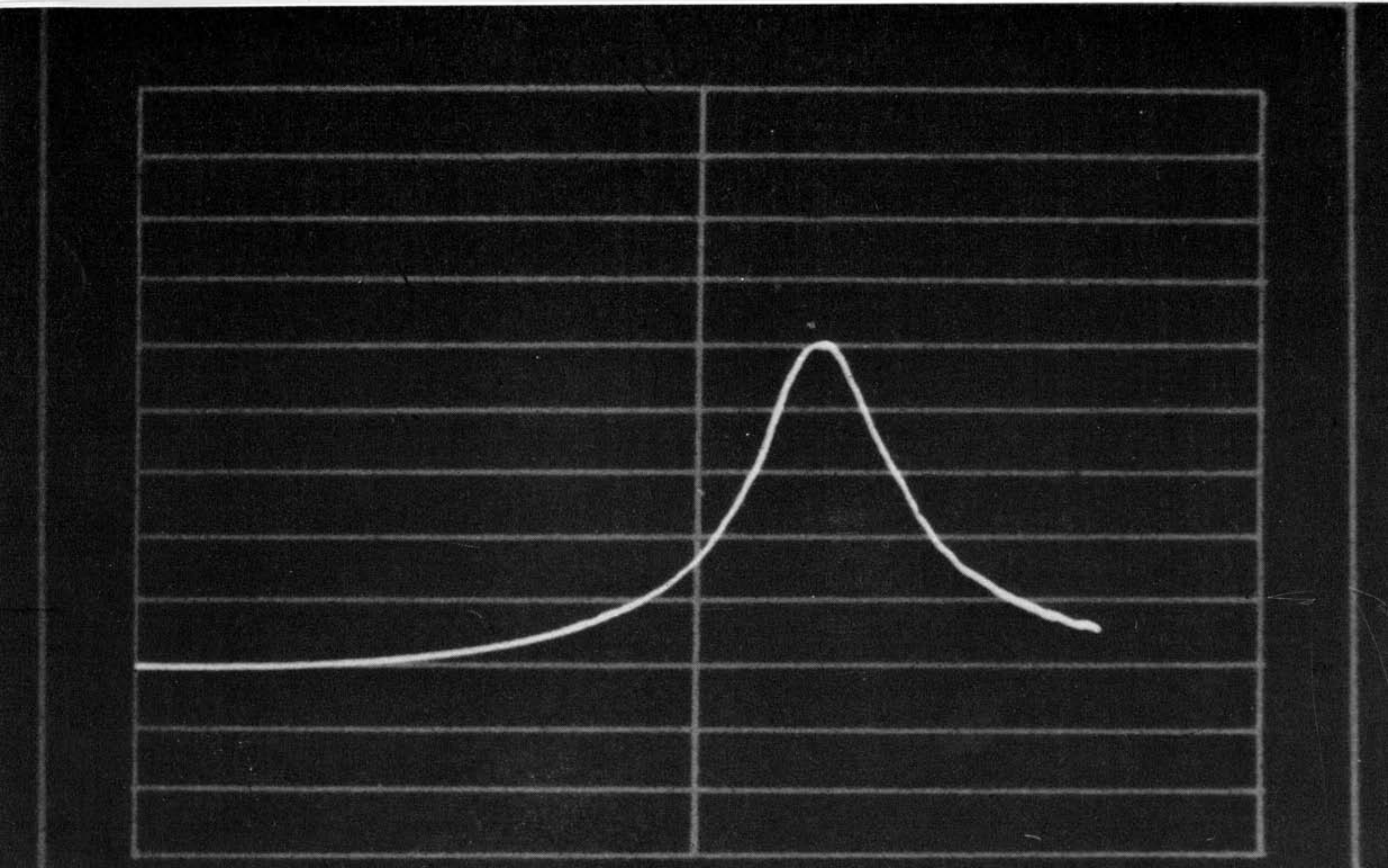
CHAPTER FOUR
THE AIR

The air rifle was preceded in history by the bow and arrow, and it is interesting to compare the two weapons because they are both similar in that the projectile is accelerated by a spring. The wooden bow being the counterpart of the coiled steel in the rifle, but there is one great difference between the two weapons, and that is that in the rifle, air is interposed between the spring and the projectile. This air is necessary because of the great difference between the mass of the tiny pellet and the heavy spring and piston; whereas in the bow and arrow, the mass of the projectile is approximately the same as that of the bowstring and the lighter sections of the bow that bend to fire the arrow. The air can be compared with the gearbox in a motor car, linking or matching the slow moving wheels and body to the light, fast moving engine.

It is very important to thoroughly understand the function of the air in a rifle, so let us take it to the extreme and imagine how we might get along without any at all. Just suppose that one was to saw the barrel off a rifle, then place a pellet directly on the top of the piston, on firing the gun the pellet would fly away with the same velocity as the piston had attained as it moved forward up the cylinder, about 50 FPS. Obviously this is very low when compared with the actual muzzle velocity, the pellet energy being correspondingly low since the pellet is so light. By the same reasoning, if one was to load the same sawn off rifle with a lead ball whose weight approximately equalled the weight of the piston, then the ball would emerge with about the same velocity as before, that is 50 FPS, but being heavier, its muzzle energy would be far higher since the energy is determined by multiplying half the mass by its velocity squared. This extra energy shows that with the heavier ball we have achieved a far better 'match' beween projector and projectile and no matching agent is required.

Having determined the reason why air is necessary, the next question that is often asked by scientifically minded air weapon enthusiasts is: "What are the pressures involved inside the air gun cylinder?" This is probably one of the most difficult parameters to measure without expensive equipment. We were, however, lucky enough to have been loaned such instruments by Messrs. Kistler Instruments Ltd. This company specializes in the measurement of high pressures by the use of PIEZO Ceramic transducers. These instruments can be made into very small robust units that lend themselves admirably to the study of internal ballistics, since they can be screwed directly into gun barrels or air rifle cylinders. The pressure transducer converts pressure into a proportional electrical charge which is processed by a charge amplifier. The resulting signal may then be displayed on an oscilloscope.

In our case, the oscilloscope trace takes the form of a curve (Fig. 4.1.) in which the vertical axis represents pressure and the horizontal represents time, not piston travel. But as explained in the previous chapter, the piston travel can be related to time, so this creates no problems when drawing a pressure/volume curve.



From these curves we are able to establish that for all practical purposes, the compression is ADIABATIC, that is, it takes place without any loss or gain or heat in to or out from the gas. These curves showed the peak pressure inside the cylinder to be in the order of 1250 p.s.i.

We have all observed that on pumping up a bicycle tyre, the pump gets hot. This is because some of the energy employed in compressing the air appears as heat. Since the pumping is done slowly and takes many strokes, the heat generated within the air travels out through the walls of the pump. Now the action of an air rifle is slightly different, in that the compression takes place so rapidly that none of the heat has time to pass into the cylinder walls. In this instance, the compression is said to be adiabatic, whereas in the case of the bicycle pump, the compression is said to be ISOTHERMIC.

Now that we have established that the compression is adiabatic, we can calculate the pressure and temperature from the following equations:—

$$P_1 . V_1^n = P_2 . V_2^n \qquad \text{..................(1)}$$

Which gives us the relationship between the absolute temperature and the volume.

Where:—

P_1 = Initial pressure
V_1 = Initial volume
P_2 = Final pressure
V_2 = Final volume
n = Ratio of the specific heat capacities of the gas, which for air.has the value of 1.408

$$T_1 . V_1^{n-1} = T_2 . V_2^{n-1} \qquad \text{.....................(2)}$$

Which gives us the relationship between the absolute temperature and the volume.

Where:

T_1 = Initial temperature of the gas in Kelvin. (i.e. Degrees Centigrade + 273)

T_2 = Final temperature of the gas in Kelvin.

Illustration opposite
4.1 Air transient

Also the work done on or by the air when the volume changes from V_1 to V_2 is given by the equation:

$$\text{Work done} = \frac{P_2 . V_2 - P_1 . V_1}{n - 1} \quad \dots\dots\dots\dots\dots\dots \quad (3)$$

Before applying any of these equations to our problems, we must first fully understand how the air is actually compressed within the air weapon cylinder. This may at first seem to be obvious, but it is in fact not quite so simple as one imagines.

When the trigger is pulled, the piston is released and is forced forward by the compressed mainspring. From the moment of release it is pushing the air inside the cylinder into a smaller and smaller space, thus causing an increase in pressure. But at a certain point the piston can no longer compress the air any further and is forced backward by it for some little distance before coming forward again, in other words, the piston bounces.

In order to understand this more fully, consider a bicycle pump that has been blocked off and made airtight. If it is now supported vertically, the handle drawn up and a weight attached, it will be noticed that on releasing the weight, the piston falls then bounces back off the cushion of air that it has compressed.

The exact same procedure takes place in the air gun cylinder only much faster, the whole cycle lasting only about 15 milliseconds; that is the time taken for a pellet travelling at 500 FPS to cover a distance of 7.5 ft.!

We have seen in Chapter One that at the point at which the piston starts its backwards bounce, the pellet releases and accelerates up the barrel. Or looking at it another way, the pellet holds back the air until a maximum pressure is reached, at which point the grip of the pellet is overcome and it starts away. At the same moment the piston can no longer deliver any more thrust to the air because of its slow speed and therefore, lack of energy, from this moment it is pushed backwards by the air in front of it. These are the events that take place when the pellet is the correct fit in a breech of optimum shape (see Chapter Six). Without these important factors, the piston travel and pellet start times are upset, resulting in lower efficiency.

The graph of the piston travel against time (Fig. 3.1.) shows the acceleration of the piston from the moment the trigger is pulled to the time that the piston hits the front end of the cylinder having bounced once on the cushion of air that it has compressed.

It is clear from this graph that the point of smallest volume corresponds with a piston position of 0.1 ins. away from the cylinder end. Since this is the point of smallest volume, it must also be the point of greatest pressure. We may now proceed to calculate the value of the peak pressure reached. Let us call this volume V_2.

Applying equation (1):

$$P_1 . V_1^n = P_2 . V_2^n$$

P_1 will equal normal atmospheric pressure, since at this point the piston has not yet started to compress the air.

V_1 is the initial volume of the air in the cylinder, that is the volume before the piston starts to move.

Since in this case the cylinder diameter was 1 inch and the piston stroke 2.5 inches we can calculate the volume:

$$V_1 = \pi r^2 h = 3.142 \times 0.5^2 \times 2.5$$

$$= 1.964 \text{ cu. ins.}$$

$$P_1 = 14.7 \text{ lbs. per sq. in.}$$

$$V_2 = \pi r^2 h = 3.142 \times 0.5^2 \times 0.1$$

$$= 0.0785 \text{ cu. ins.}$$

$$P_2 = ?$$

Thus:

$$14.7 \times (1.964)^n = P_2 \times (0.0785)^n$$

or:

$$P_2 = \frac{14.7 \times (1.964)^n}{(0.0785)^n}$$

$$= 14.7 \left(\frac{1.964}{0.0785} \right)^n$$

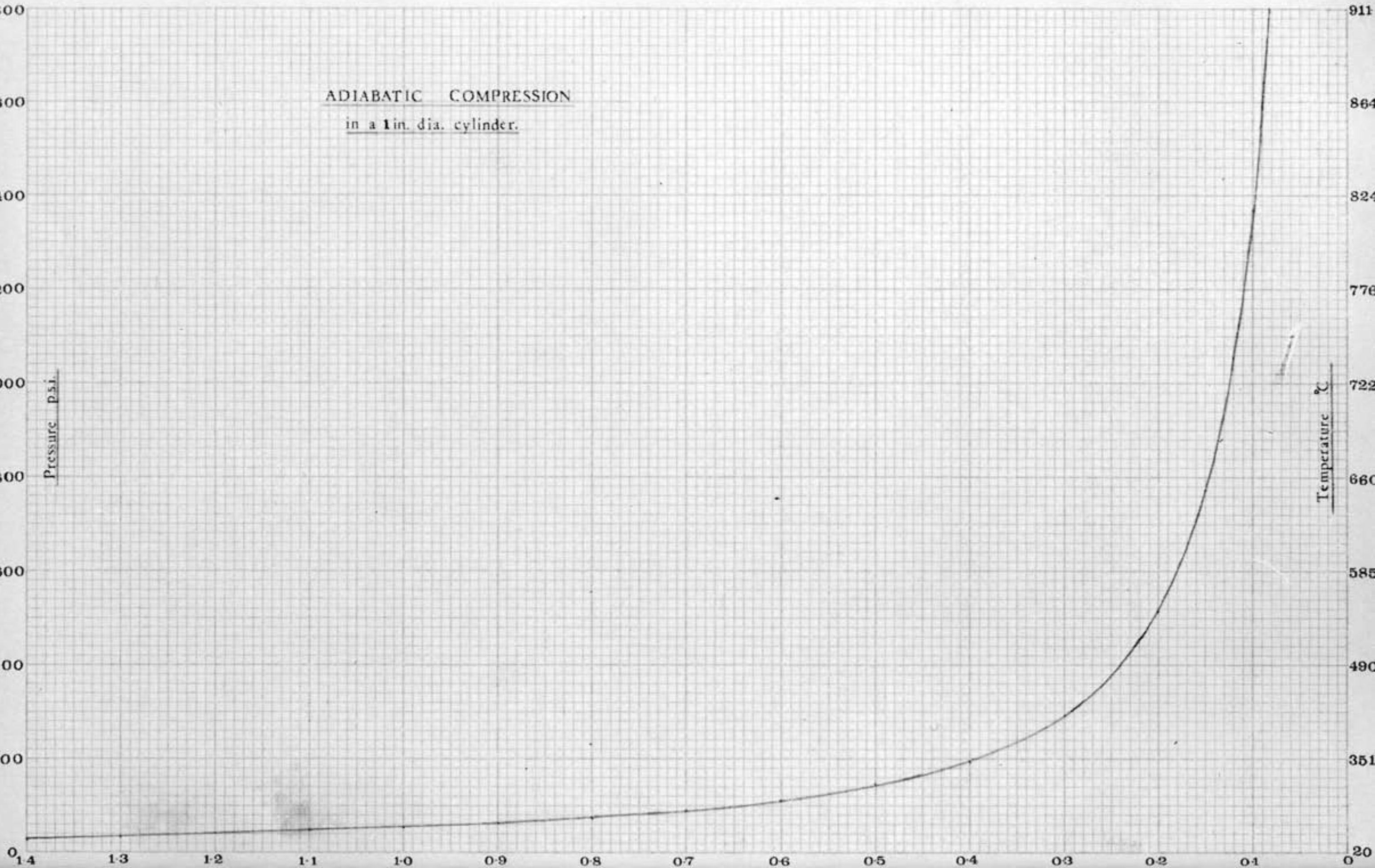
Since $n = 1.408$

$$P_2 = 14.7 \times 92.961$$

Thus:

$$P_2 = 1366 \text{ lbs./sq. ins.}$$

Since the above calculations cover a typical, rather than a particular case, the lost volume of the transport port has not been taken into account. This is because, during our experiments, the size and shape of the port were altered. But it would be a simple matter to establish the volume of the port and add the figure to V_1 and V_2 at the start of the calculation.


ADIABATIC COMPRESSION
in a 1 in. dia. cylinder.
Pressure p.s.i.
Temperature °C
1800
1600
1400
1200
1000
800
600
400
200
0
911
864
824
776
722
660
585
490
351
20
1·4
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0

This value of P_2 is therefore, the maximum pressure reached inside the cylinder. It must, however, be emphasised that this pressure is only reached for an instant and only the slightest backward movement of the piston causes a dramatic drop in pressure. If one looks at the adiabatic curve drawn in Fig. 4.2, one will realise that a backward movement of only 0.02 ins. drops the pressure from 1350 to 1000 psi ! ! And a further drop in pressure to about 500 psi is brought about if the piston moves back only 0.1 inch.

When the piston accelerates forward, the Kinetic Energy that it contains is not only used in compressing the air but also, unfortunately, in heating it up. Thus the temperature increases tremendously with the exponential rise in pressure. The new temperature can be calculated from equation (2).

$$\begin{aligned} T_1 . \ V_1^{n-1} &= T_2 . \ V_2^{n-1} \\ T_1 &= \text{Room temperature} = 20^\circ \text{ C} \\ &= 20 + 273^\circ \text{ K} \\ V_1 &= 1.964 \text{ cu. ins. (as before)} \\ V_2 &= 0.0785 \text{ cu. ins. (as before)} \\ T_2 &= ? \end{aligned}$$

Thus:

$$293 \times (1.964)^{n-1} = T_2 \times (0.785)^{n-1}$$

or:

$$\begin{aligned} T_2 &= 293 \times (25)^{1.408-1} \\ &= 293 \times 3.718 \\ &= 1098 \text{ K} = (1089 - 273)^\circ \text{ C} \\ &= 816^\circ \text{ C} \end{aligned}$$

At this temperature it is easy to see why oil in the cylinder ignites, and a gun is said to be "dieseling".

Once again we must emphasise that this temperature, like the pressure, is only reached for a fraction of a second. The rise in temperature can be seen against piston travel on the right hand side of Fig. (4.2.).

It was said in our definition of an adiabatic compression, that no heat enters or leaves the gas, as is the case with the air weapon. Although the temperature of the air has risen, the rise is solely due to the increase in internal energy, and not to any transference of heat. There just is not time for a significant transfer to take place !

Illustration opposite
4.2 Adiabatic compression graph

If the piston were imagined fixed in its extreme forward position for some time, then heat would leak away through the cylinder walls, until the air temperature became equal to that of the surroundings. The compression would no longer be adiabatic. As the temperature drops, so too would the pressure—even assuming no leakage. It would drop, in fact, to the pressure that would be expected from an isothermic compression of the same magnitude.

We are now in a position to calculate the actual amount of work done on the gas as it is compressed by the piston.

Thus, using equation (3);

$$\text{Work done} = \frac{P_2 V_2 - P_1 V_1}{n - 1}$$

Using the previous figures for pressure and volume:

P_1 = 14.7 psi
V_1 = 1.964 cu. ins.
P_2 = 1366 psi
V_2 = 0.0785 cu. ins.
n = 1.408

Thus:

$$\text{Work done} = \frac{(1366 \times 0.0785) - (14.7 \times 1.964)}{1.408 - 1} \text{ inch pounds}$$

$$= \frac{107.3 - 28.867}{0.408} \text{ in. lbs.}$$

$$= \frac{78.432}{0.408} \text{ in. lbs.}$$

$$= 192.235 \text{ in. lbs.}$$

$$\text{or } \frac{192.235}{12} \text{ Ft. lbs.}$$

$$= 16.0 \text{ Ft. lbs.}$$

We can now see that the total energy required to compress the air to 1366 psi is 16 ft. lbs. of energy, this must, therefore, be the total amount of energy contained by this air at the stated pressure. It must, however, be noted that at these high pressures, a drop of only 64 psi. means a decrease of one foot pound in energy.

If the piston remained in this forward position, the full 16.0 ft. lbs. would be available to propel the pellet up the barrel, but instead, the piston bounces back from this point using up some of the energy. The amount used can be calculated from the same adiabatic equations as before, but this time for an expansion. The calculations are, however, complicated by the fact that as the piston moves back so the pellet accelerates forward up the barrel. We must, therefore, account for the extra volume behind the pellet.

The piston bounces back a distance of 0.4 inches away from the cylinder end, and the pellet in this time reached a distance of 7 inches from the breech.

Then from equation (1):

$$P_1 V_1^n = P_2 V_2^n$$

$$\begin{aligned} P_2 &= 1366 \text{ psi} \\ V_2 &= 0.0785 \text{ cu. ins.} \\ P_1 &= ? \\ V_1 &= \text{Volume in cylinder} + \text{Volume in barrel} \\ &= (\pi \times (0.5)^2 \times 0.4 + (\pi \times (0.11)^2 \times 7) \text{ cu. ins.} \\ &= 0.3142 + 0.2661 \text{ cu. ins.} \\ &= 0.5803 \text{ cu. ins.} \end{aligned}$$

Hence:

$$P_1 \times (0.5803)^{1.408} = 1366 \times (0.0785)^{1.408}$$

Thus:

$$P_1 = 1366 \times \left(\frac{0.0785}{0.5803} \right)^{1.408}$$

$$P_1 = 81.7 \text{ psi}$$

This is the pressure in the system when the piston has bounced back.
Now applying the equation for the work done on or by a gas, equation (4):

$$\frac{P_2 V_2 - P_1 V_1}{n - 1} = \text{Work done}$$

$$\frac{(1366 \times 0.0785) - (81.7 \times 0.5803)}{1.408 - 1} = \text{Work done (in. lbs.)}$$

$$= 146.6 \text{ in. lbs.}$$

$$= 12.2 \text{ foot pounds}$$

(This is the energy given up by the air in its expansion).

Subtracting this from the 16.0 ft. lbs. that the air contained when the piston was 0.1 ins. from the cylinder end, we obtain the amount of energy remaining in the air, i.e. 3.8 foot pounds.

We must now consider where the 12.2 ft. lbs. given up by the air has been distributed. From the spring energy curve (Fig. 21.) we can determine that 1.9 ft. lbs. was used in compressing the spring 0.4 inches. This was effectively wasted since the compression of the spring served no useful purpose. We also know that when the pellet is 7 inches up the barrel, it is moving with a velocity corresponding to an energy of 5.8 ft. lbs. (see Fig. 6.1). Thus we are left with 4.5 foot pounds that we have not been able to account for, we will, however, endeavour to explain this loss later, in terms of shock waves and the like.

CHAPTER FIVE
THE TRANSFER PORT

The transfer port is that small but extremely important passage that joins the inside of the cylinder to the bore of the barrel. This passage has, over the years, suffered many design changes, it has been drilled to a variety of sizes, and at angles to suit the gun layout.

When investigating this particular topic in the air rifle, there are three main variables to be considered:—

(1) The diameter of the port.

(2) The length of the port.

(3) The shape of the port.

Before discussing these points, however, let us first consider exactly what happens when the air rushes through this passage. As the piston streaks forward, pressure is built up behind the pellet, the pellet then releases its grip and accelerates off up the barrel at the moment of peak pressure in the cylinder (if it is a well fitted pellet). As it accelerates, the pressure immediately behind it falls, the high pressure air in the cylinder then rushes through the port to equalise the pressure, hence an airflow has been created from the cylinder to the barrel. This pressure difference must be maintained to preserve the airflow. But, to accelerate the pellet, the flow must increase, and this can only be achieved by a continuously increasing pressure difference between the pellet base and the cylinder.

When the pressure on the barrel side of the port drops to about half of the cylinder pressure, a condition known as "critical flow" is set up. At this point, the airflow through the port is brought to a constant velocity and cannot be further increased without raising the cylinder pressure. But the cylinder pressure is already falling due to the backward movement of the piston and forward motion of the projectile, this means, therefore, that the pellet can no longer be accelerated. It may, however, be pushed along at a constant velocity since although the flow cannot increase it will not necessarily decrease.

The only way in which the rate of flow may be improved upon is by raising the peak cylinder pressure or, maintaining the existing pressure for a longer time by holding the piston in the forward position. Our efforts in this direction have already been described and it is clear that it is "easier said than done".

At the time that the critical flow is reached, shock waves are formed in the transfer port; because, under these conditions, the velocity of the air flow is equal to that of sound for the pressure and temperature within the port. The effect of these waves will be dealt with further in the chapter on efficiency, it is sufficient at this point, however, to be aware of their existence in the transfer passage.

It should be clear from the foregoing that it is of vital importance that there should be as little restriction as possible to the air flow so that the pellet obtains the maximum acceleration before critical flow is reached.

Let us now discuss the three points mentioned earlier, since maximum airflow depends upon the format of this port.

The diameter of this port is obviously somewhat dependent on the calibre of the gun, if the port were larger than the calibre there would be a danger that the pellet might get drawn back into the cylinder. To determine the most efficient port diameter for our particular gun, we adopted a system of trial and error. This involved the drastic operation of machining out the existing port to a diameter of about three eighths of an inch. Then machining a series of interchangeable ports, each identical apart from their bore diameters, which were machined to individual sizes, ranging from 1/16″ up to 11/64″. The rifle chosen for all these experiments was of the break barrel type, it was, therefore, possible to use an "O" ring to both seal the breech and hold the false port in position.

With this system we were able to experiment with each port size as many times as we wished whilst ensuring similar conditions. The following table lists the port diameters together with the average velocities obtained with each size, the calibre being .22″.

Port Diameter (ins.)		Average Velocity
1/16	(0.0625)	334 fps
5/64	(0.078)	388 fps
3/32	(0.094)	420 fps
7/64	(0.1094)	424 fps
1/8	(0.125)	428 fps
9/64	(0.41)	425 fps
5/32	(0.156)	423 fps
11/64	(0.172)	414 fps

From these results it is clear that the optimum port diameter in this case is about 1/8″. Either side of this diameter the velocity immediately becomes lower, for smaller diameters this is easily understood, since a small hole offers far more resistance than a large one which will allow a greater mass rate of air flow through it. The reason for the velocity falling when using a port diameter greater than 1/8″ is less easily understood. It is probable that much above this figure an unacceptable amount of "lost volume" is produced, resulting in a decrease in the final pressure, and therefore, a reduction in the accelerating force behind the pellet.

Chapter Five—The Transfer Port

"Lost volume" is a term we use to describe the volume of air contained by the transfer port and other holes or recesses in the piston head. Taking an extreme case to illustrate the point, suppose that the lost volume amounted to a large fraction of the total volume swept by the piston. The piston would then accelerate forward and hit the end of the cylinder since there would not be a large enough pressure build-up to arrest it, neither would the pressure be great enough to start the pellet off up the barrel. It will be noticed that the maximum port diameter tested was 11/64″, this was because a further increase resulted in the piston actually hitting the end of the cylinder.

The length of the port is far more difficult to alter or experiment with, but it is obvious that the shorter it is the better, as it then produces less lost volume. Also being short there is less resistance to air flow due to wall drag on the air as it rushes through the passage.

Air, like any other fluid, has viscosity. Viscosity is the property of a fluid which makes it resistant to flow. Compare treacle emerging from a tin to the flow of water from an upturned bucket. Air is, of course, not as viscious as water, at normal temperatures and pressures. But it obeys the same laws of fluid flow, hence its viscosity increases as the pressure rises. Since, in the main, we are dealing with high pressures, energy losses due to this action could be significant.

In order to get a practical idea of what happens at the port, it is helpful to imagine air to be liquid. With this thought in mind, it is not difficult to remember how the flow of a stream is impeded as it flows over a rocky bed. The sharp edged stones form waves and eddies that restrict the smooth passage of the water. In a similar way, most of the rifles that we have looked at have a sharp edge at the entry to the port, since it is simply a drilled hole. Now there is nothing better than a sharp corner for upsetting the flow of a fluid and causing eddies, restricting the air flow. In fact, it would be true to say that a sharp corner was the opposite of streamlining. This edge is therefore, a part of the system where energy is liable to be lost.

Again, practical experiment was the only method open to us to investigate the energy losses at the entry port. We took one of the false ports and shaped the entry to a bellmouth. This immediately increased the velocity of the experimental gun by seven feet per second. Other guns that we have modified in this way have produced better results than this, which goes to prove that the shape and size of the port is individual to each gun.

So, what is best? Well, very often the designer of any spring air weapon is "between the devil and the deep blue sea" in this area. What is required is the shortest possible length of optimum diameter port with a smooth lead-in for the air, and, incidentally, a polished surface throughout. Unfortunately, however, it is not always possible for the port to be short without losing physical strength in that area, especially in the design of barrel cockers. The production of a bellmouth at the entry end of the port is a refinement that is not often encountered on mass produced rifles. From a purely theoretical point of view, the best possible shape for a transfer port would be a bellmouth at the entry followed by a venturi which contracts at the centre to a diameter slightly smaller than the calibre, then opens out again to a diameter that corresponds with the mouth at the entry to the bore of the barrel. However, after going to the trouble of making such a device, we were disappointed to find the practical advantages were insignificant.

Some break models are fitted with a breech sealing washer positioned in a recess cut into the end of the transfer port, there is a danger here that some energy will be lost at this point, since it is unlikely that the airflow will remain smooth as it passes through the washer. The hole in the washer usually being larger or smaller than the bore of the port.

One well known make of high performance tap loading rifle at one time had a funnel shaped end to the cylinder, giving a streamlined flow of air from the cylinder to the barrel. The piston had a cone shaped end to coincide with the angle of the funnel. Another great advantage of this system was that the transfer port was exceptionally short, since the tap was positioned directly at the apex of the funnel. The whole point of the design was that losses in this area were kept to a minimum. Unfortunately, one can only presume, the manufacturing costs outweighed the velocity increase.

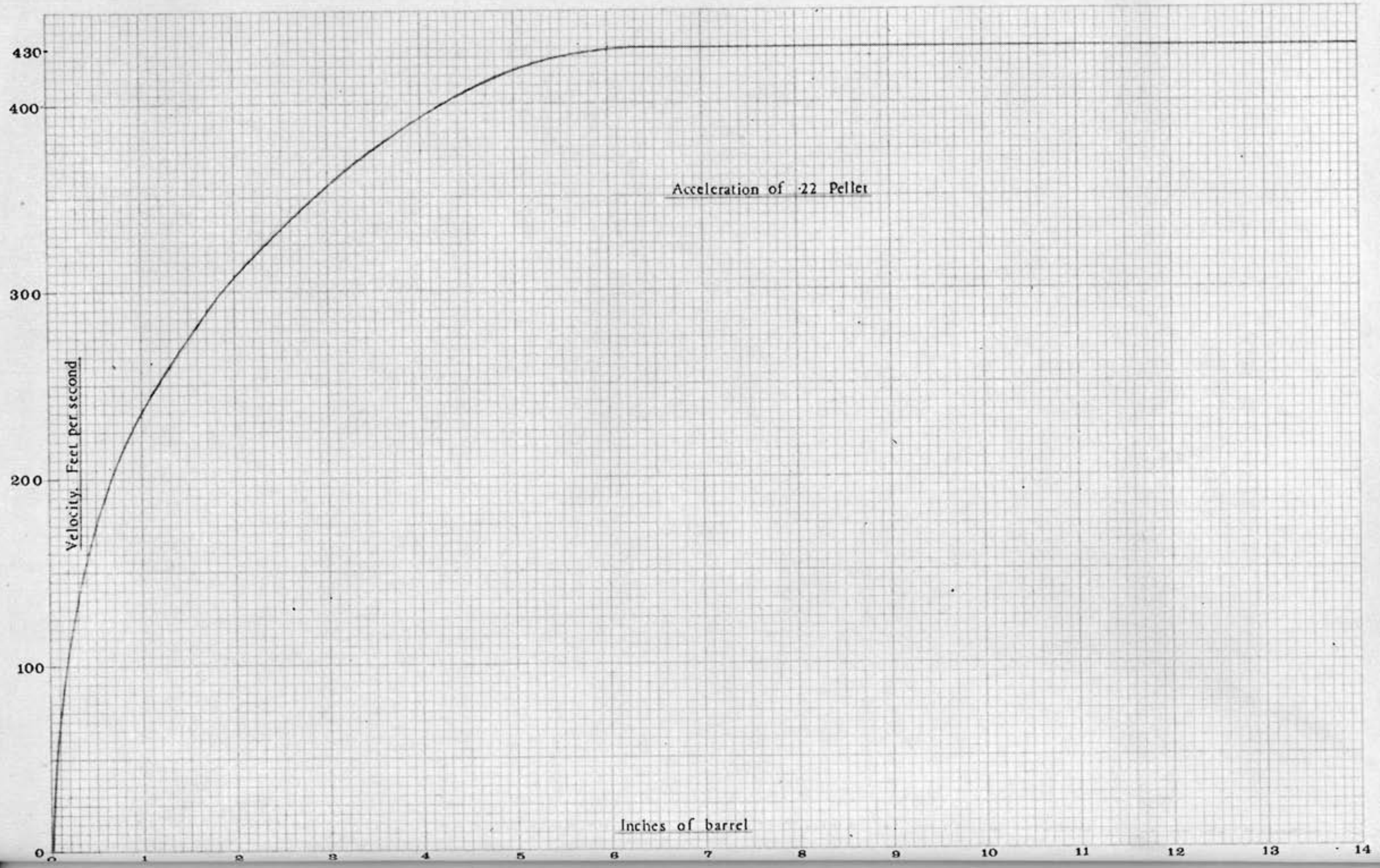
CHAPTER SIX
THE BARREL

When we speak of the barrel of an air weapon, we mean the whole tube extending back from the muzzle to the breech at the point where the pellet is seated ready for firing. Although it may seem unnecessary to make such an obvious definition, we have done so because we want to make it quite clear that we have included the section of the bore that holds the pellet before "blast off". It is, in fact, this small part that helps to determine the consistency of the weapon, but more of this later, let us first have a look at the controversial topic of the barrel length.

We went to a great deal of trouble over the study of barrel length as soon as we realised that much of the current thought on air weapons was being derived from firearm principles, this comparison is completely unscientific as are any other internal ballistic comparisons between firearms and air weapons. In the case of the firearm, the projectile is under acceleration along the whole length of the barrel. This action has been arranged by the design of the propellant in the cartridge which has been carefully made to burn itself up in the time that the projectile is in the bore. This being so, the gases produced by the combustion of the propellant charge keep up a constant pressure on the base of the bullet giving it enormous energy. Unfortunately, the air weapon is severely handicapped at this point since there is only a very limited amount of energy to accelerate the pellet and that is virtually all imparted to the pellet in the first five inches or so of the barrel. After this distance, the pellet neither loses nor gains speed until it has covered a further twenty five inches or so, after which it begins to slow up due to friction from the barrel wall and also on account of the volume of air that it is pushing ahead of itself. From this, it is clear that an air gun with a long barrel is not more powerful than its shorter counterpart. This statement is based on the graph Fig. 6.1., which shows the acceleraton of a .22 pellet up a barrel. From this diagram it can be seen that the pellet is accelerated during the first five inches of its travel only, the remainder of the journey was accomplished at a steady velocity.

The reason for this stable velocity is that critical airflow has been set up through the transfer port due to the reduced pressure in the cylinder. This critical flow as already mentioned in the previous chapter, means that the air can now only flow at a certain speed, hence the pellet is only pushed at a steady rate and not accelerated.

The graph in Figure 6.1 was arrived at by the use of the very odd looking barrel shown at the bottom of Fig. 6.2. It had holes drilled in its wall at one inch intervals all along its length, into each of these holes an insulating bush was screwed and each of these bushes carried a small screw that was pointed at the end and just entered the barrel. With this strange device it was possible to make contact with the pellet at any desired points along the barrel, since, as the pellet passed any screw that had been adjusted into the bore, electric contact was made between the screw and the bore at that point. Coupling this device to our electronic chronograph, it was possible to establish the time taken


Acceleration of ·22 Pellet
Velocity. Feet per second
Inches of barrel
430
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

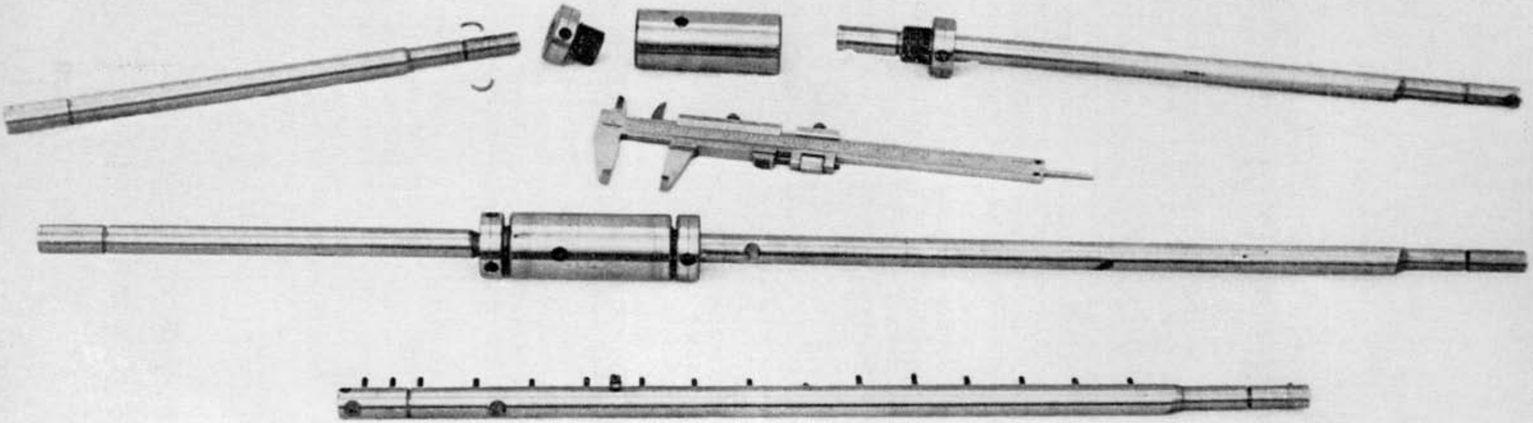
for pellets to traverse various sections of barrel. This experimental piece of equipment could be coupled up to any number of sections of the extendable barrel shown in top of Fig. 6.2. By this process, we were able to study bores of up to five feet in length. At these extended lengths, the velocity had fallen to an utterly useless figure, but the experiment was well worthwhile since it proved beyond doubt that a long barrel is not the key to high velocity.

It might not be out of place, at this point, to say a few words about the other types of air weapons, such as pneumatics and CO_2 guns that rely upon a reservoir of pre-compressed gas to accelerate the bullet. Although we have not made a detailed study of such weapons, it would seem to be very clear that they fall into a class of their own as regards internal ballistics. They cannot be grouped with firearms since no chemical burning takes place to provide energy, the only push the pellet can get is from the expansion of the gas allowed through the valve when the trigger is pulled. There is usually quite a large volume of gas admitted at each discharge, so a long barrel is an advantage, as it gives plenty of time for the gas to expand and transfer its energy to the pellet. In all probability some of the CO_2 that is passed through the control valve is still in a liquid state and therefore requires heat in order to convert to gas and expand. It can only gather this heat from the walls of the barrel, and therefore, the longer the barrel, within reason, the more efficient will be the conversion of the energy contained in the gas to pellet propulsion.

Now, the guns that are powered by compressed gas cannot be grouped with spring powered weapons, the spring weapon being unique in that it relies on the pellet being a tight fit at the beginning of its journey in order to develop a pressure behind itself. This ability of a pellet to grip the barrel whilst the piston builds up pressure, and then to release at the correct critical moment is probably the most important factor in the performance of a spring rifle. Anyone who has ever owned an air weapon will have been advised to try "this" or "that" brand of pellet, because they performed so well in such-and-such a rifle. The whole idea of experimenting with different types of pellet is to find a make that releases in that particular barrel at the instant of highest pressure.

Once we realised the importance of this point, we set about investigating it in great detail. First of all, we checked what we call the "static" pressure required to start the pellet down the barrel through various breech shapes. We conneced short lengths of barrel to a hand operated oil pump in such a way that we could increase the pressure behind the pellet very gradually, whilst at the same time, being able to watch the rise in pressure on a gauge. As the pressure reached the point at which the pellet released and moved forward up the tube so the pressure gauge needle fell, the maximum pressure obtained in each case being noted.

Illustration opposite
6.1 Acceleration of 0.22 pellet



Each length of barrel had a different shape machined at its breech so it was not difficult to compare the static release pressures of the various tubes when fitted with standard pellets. It was also possible to investigate the pressures attained by pellets with expanded or collapsed tails. After checking this factor, each barrel was then mounted on the experimental gun and its performance measured with the chronograph. It must, however, be emphasised that this is the experimental static starting pressure only, and that this hydraulic test is done on a much slower time scale than the one witnessed inside the gun. The actual starting pressure (dynamic) being approximately three times this value.

The results, all the average of 20 shots, are recorded below:

	Static Pressure	Velocity
Sharp right angle breech.	374 p.s.i.	371 f.p.s.
Slight radius at breech.	444 p.s.i.	434 f.p.s.
45° chamfer at breech.	442 p.s.i.	373 f.p.s.
60° chamfer at breech.	399 p.s.i.	390 f.p.s.
Slow taper into barrel.	308 p.s.i.	292 f.p.s.

It is clear from these results that a static pressure in excess of 440 p.s.i. is required to produce maximum velocity and that is attained by a polished radius

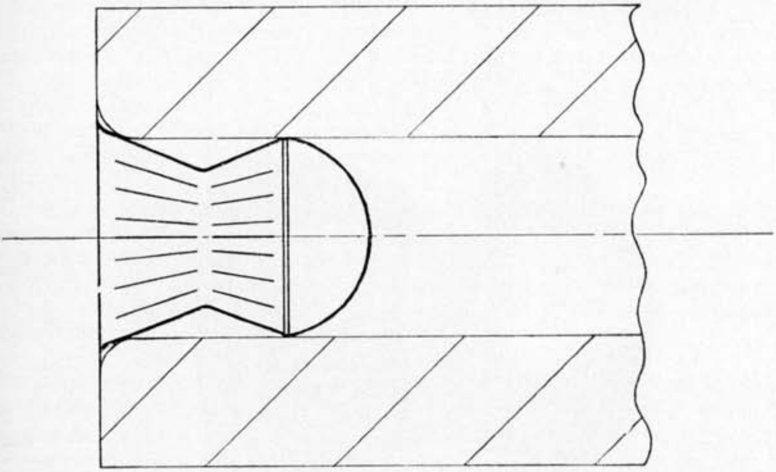
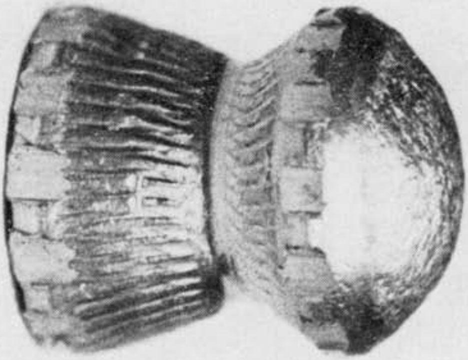
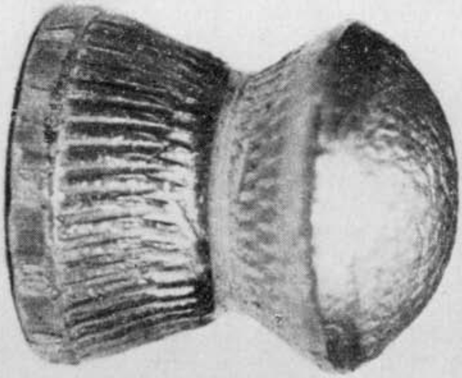


Fig. 6.3. Pellet in breech

Illustration opposite
6.2 Experimental barrels





at the breech. This is illustrated in Fig. 6.3. It is, however, possible to have a pellet too tight in the breech, resulting in it not starting until after the peak pressure is reached, producing a lower muzzle velocity. This fact can be proved by expanding the skirts of pellets beyond reasonable dimensions, then checking their velocities. Now the reason that the sharp right angled breech produced a low pressure and therefore low velocity was because, instead of re-forming the tail of the pellet it sheared a ring of lead from the skirt, this shearing of the tail must obviously require less force than re-forming it into the bore.

We concluded from these experiments that at the moment of firing, the tail of the pellet must first grip the end of the bore, then as the pressure behind it rises, the skirt is collapsed until it becomes the same dimension as the bore, at which point it releases and is accelerated up the barrel with the maximum pressure behind it.

An added bonus arises from the correct breech formation; the final velocity is far more consistent. We found the variation over a number of shots to be 2% with the correct shape, whilst the others showed a figure in the region of 6%. This was obviously a worthwhile improvement. It is probable that this 2% variation is due to differences between pellets.

The value of spending a little time experimenting with different makes of pellet can best be shown by the photograph of two pellets Fig. 6.4. This shows the result of passing identical pellets through differing barrels. The one on the left shows deeply printed rifling on the head, the tail being so tight in the bore that the lead has been dragged backwards—plainly a case for a smaller brand of pellet. Now the one on the right of the illustration carries a very slight rifling print on its head but a well marked tail. This pellet was a good fit in the barrel concerned and will have given maximum velocity.

A good guide to determine the fit of a pellet is to try it into the muzzle of the gun in question, if it just enters without undue force and can be withdrawn to leave a slight print, then it has a fair chance of being the correct sized pellet for that bore. If on the other hand it is unduly tight or slack, try another brand. At the same time one must watch out that the tail of the pellet is sufficiently large a diameter to grip the breech correctly.

A point to bear in mind when carrying out the above test is that some rifles of continental manufacture have what we call a "pinched barrel". In this configuration the bore is constricted for the last inch or so, this rather surprising choke reduces the diameter by about four thousandths of an inch. We have been told that although the velocity is reduced by this formation, the accuracy

Illustration opposite
6.4 Two pellets

is increased. Since accuracy is outside the scope of this present work, we have not attempted to verify this claim.

The majority of our present work was done using smooth bore barrels. This made for simplicity when coupling the various lengths together and, of course, ease of manufacture, but we obviously had to compare some of the results with a rifled barrel since energy is required to set the pellet spinning, and this energy must appear at the expense of the muzzle velocity. We were surprised to find that so little energy is required to spin the pellet that it was impossible to detect the loss in velocity when using a rifled bore. One point that is perhaps worth mentioning in this chapter, is that barrels are, of course, rifled in order to increase accuracy by gyroscopic action through spinning the pellet. We noticed, however, that all the pellets from our smooth bore tubes landed correctly, nose first, and in exactly the same place as those fired from the rifled barrels! Which makes us wonder if rifling is really necessary when using diabolo pellets which apper to have self righting abilities. Food for thought and future investigations . . . .

However, as a final thought whilst on the subject of barrels, it is interesting to consider for a moment the gun that is all barrel and very little else, the blow pipe. The incredible feats of range and accuracy with which they are credited are made even more surprising when one realises that it is difficult to produce even one pound per square inch pressure when blowing into the pipe. Yet tribesmen are reported to be able to kill small birds and animals at considerable ranges without the use of poisoned darts. The secret being that the blow pipe relies on its length and the size of the hunter's lungs to produce a useful velocity. Whereas the spring operated air rifle employs a tight fitting pellet to produce a small volume of highly compressed air behind itself, the blow pipe missile is a very loose fit in the bore to enable the hunter's lungs to maintain a constant acceleration all the way up the pipe. In other words, it relies on a large volume of air at steady low pressure rather than a small volume at high pressure.

No doubt the pipe length has been developed to the maximum to suit the size of the hunter's lungs, whilst at the same time keeping the volume small by reducing the calibre to the smallest practical size that can be made. The weight of the dart has also been developed by trial and error, but the success of the final combination is world famous.

CHAPTER SEVEN
RECOIL

This chapter is all about very little indeed, in fact, we rather wondered if it was worth writing at all. But since we have been to the trouble of investigating the recoil of an air rifle, some readers may find the results to be of interest.

It has often been said that one of the chief advantages of any air weapon is that it has no recoil. Such a statement is just not true, every air gun has a certain amount, but in most cases it is so small as to be insignificant. In Mr. Wesley's book, he tells of an amusing adventure with a very large calibre air cane, the recoil from which was great enough to nearly knock him over. In the small bore spring operated weapon of today, the weight of the projectile is so small that the recoil cannot be felt when the gun is fired, in fact, the small amount that does exist is usually completely masked by the jerk from the piston as it accelerates down the cylinder and then bounces back on the cushion of air.

Another point about the recoil that often causes confusion is the moment that it actually occurs. It is often said that the weapon does not move until the shot leaves the barrel, again this is not true. The backward motion of the gun starts the moment that the projectile begins its journey up the barrel. In order to make this as clear as possible, imagine a gun that has been made out of the lightest material available, it is loaded with a projectile that is made from the heaviest possible substance. It is perfectly obvious that at the instant of firing, the gun will try to move backwards away from the projectile and that the recoil will have started at that point. It will not wait until the projectile leaves the barrel, in spite of a lot of arguments to the contrary.

In a sporting rifle that employs a very high pressure cartridge, there is a rocket effect caused by the energetic blast of the gases as they emerge from the muzzle. This adds to the mule-like kick of such a weapon, but has no significance in the world of air weapons.

There is third cause of recoil, which again can be ignored as regards to air weapons. Since the pellet is being accelerated up the barrel, causing recoil, so also is an amount of air being pushed along after it. This air has a definite masss and must therefore cause recoil.

So now for a bit of theory on the subject, why should recoil occur at all? It all stems from Newton's third law of motion which states: "To every action there is an equal and opposite reaction". We have already established that there are three factors involved. The first is the acceleration of the pellet from its state of rest to the velocity it reaches as it exits the muzzle of the gun. The second is the blast of air at the muzzle as the pellet emerges. This can be clearly seen in Fig. 9.8. The third is the acceleration of the air up the barrel behind the pellet. The velocity of which must be assumed to be approximately half that of the pellet. But again the recoil resulting from this small amount or air has no measureable effect on the weapons under discussion.

Let us now consider the first of these three elements in further detail, that is the reaction to the forward acceleration of the pellet. By Newton's third law, the pressure driving the pellet forward up the barrel exactly equals the pressure driving the gun backwards, causing the recoil, and they can both only act for the time that the pellet remains in the barrel. Now by the principle of the conservation of linear momentum; the motion of the pellet forward in feet per second multiplied by its mass is equal to the rearward motion of the gun in feet per second multiplied by its mass.

If;

The mass of the gun = M
The mass of the pellet = m
Velocity of the gun = V
Velocity of the pellet = v

Then the conservation of momentum:

$$m \times v = M \times V$$

$$\text{Since mass} = \frac{\text{Weight}}{\text{Acceleration of gravity}} = \frac{W}{g}$$

Thus we have:

$$\frac{wv}{g} = \frac{WV}{g}$$

Where:
W = Weight of Gun
w = Weight of pellet

Because g is constant and the same for both gun and pellet.

Then:

$$w.v. = W.V. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Thus:

$$V = \frac{w.v.}{W}$$

We may now calculate the velocity of the recoil, and hence the energy imparted to the gun by the reaction from the pellet's acceleration.

Weight of gun (W) = 6.625 lbs.
Weight of .22 pellet (w) = 0.00214 lbs.
Velocity of pellet (v) = 430 ft/sec.

Substituting values:

$$V = \frac{0.00214 \times 430}{6.625} = 0.1389 \text{ ft./sec.}$$

From the equation for energy:

$$E = \frac{W.V.^2}{2g}$$

Where W is the weight and V is the Velocity.

$$E = \frac{6.625 \times (0.1389)^2}{2 \times 32.16}$$

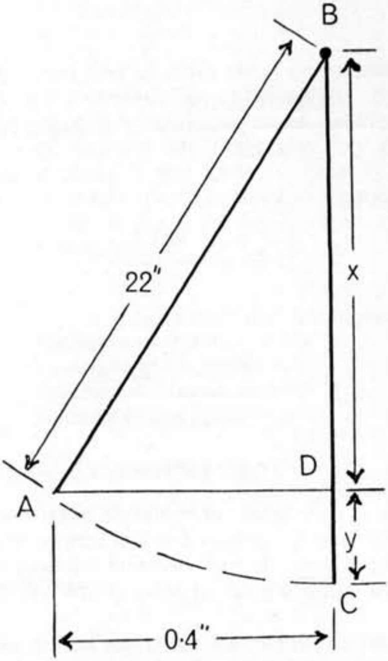
$$E = 0.001987 \text{ ft. lbs.}$$

This is obviously a very small and insignificant amount of energy when compared with the total energy contained in the spring, or even when compared with that in the moving pellet. It can therefore be omitted from most air rifle calculations since other variants such as pellet shape will have more effect.

Being practical sort of people, we could not let the whole recoil investigation depend upon a purely mathematical solution, so we set up the gun to give us some practical results. We suspended it by two sets of cords from a beam in such a way that the barrel was level and remained so during the recoil swing. We then fixed a pointer to the side of the weapon and placed a scale in a fixed position beside it, from then on it was a simple matter to photograph the scale and pointer at the moment of firing to determine the exact amount of recoil. We fired the gun by means of a solenoid mounted on the butt, the solenoid being positioned so that its movements had no effect upon the recoil readings.

Upon firing, the gun swung backwards and forwards like a pendulum, since the length of the supporting cords are known and the amount of the backward swing can also be measured, the application of some more mathematics will show how much energy is being expended in recoil. It will be obvious from equation (1) that a light 0.177 pellet will produce less swing, and therefore, recoil, than the heavier 0.22 pellet. From our experiments we found that a 0.22 pellet weighing 15 grains produced a swing of 0.4 inches on our rifle weighing 6.625 lbs. when it was suspended by cords 22 inches long.

In the diagram overleaf, the maximum backward horizontal movement is 0.4 inches thus AD = 0.4 inches and BA and BC being the length of the supporting cords is 22 inches.



Distance CB = (y + x) = 22 ins.

Since triangle ABD is a right angled triangle then by Pythagoras:

$$AB^2 = BD^2 + AD^2$$

Therefore:

$$22^2 = x^2 + 0.4^2$$

And:

$$x^2 = 22^2 - (0.4)^2$$

Also:

$$\begin{aligned} \text{Since } 22 &= (y + x) \\ x &= 22 - y \\ x^2 &= (22 - y)^2 \\ x^2 &= 22^2 - y^2 - 44y \end{aligned}$$

Substituting from the equation $x^2 = 22^2 - (0.4)^2$

$$22^2 - (0.4)^2 = 22^2 - y^2 - 44y$$

or:

$$y^2 - 44y + (0.4)^2 = 0$$
$$y^2 - 44y + 0.16 = 0$$

This is now a quadratic equation in y. If we apply the well-known equation for the roots of quadratics, i.e.:

$$y = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

In our case $a = 1$, $b = -44$, and $c = 0.16$

$$y = \frac{44 \pm \sqrt{44^2 - 4 \times 1 \times 0.16}}{2 \times 1}$$

$$= \frac{44 \pm \sqrt{1936 - 0.64}}{2}$$

$$y = 0.0036367 \text{ ins.}$$

or

$$y = 0.0003 \text{ ft.}$$

Since y is the maximum height to which the gun was raised, then the potential energy that it had at this height was its weight multiplied by this height.

$$= W \times y$$
$$= 6.625 \times 0.0003$$
$$= 0.002 \text{ ft. lbs.}$$

Thus, this is the total amount of energy used in pushing the rifle backwards, established by experiment. It is so small that it can be neglected when considering energy losses as a whole. It is, however, interesting to note that this figure is very slightly larger than the calculated figure arrived at earlier. That was for the reaction due to the acceleration of the pellet alone. The difference between the two figures is probably produced by the "rocket effect" of the air escaping after the pellet has left the muzzle. The very small recoil caused by this effect can obviously only be determined experimentally and cannot be detected by the shooter.

We then decided to try and isolate the "rocket effect" by a practical experiment. We made a muzzle brake and fitted it to the end of the barrel, this device used by the military to reduce the recoil of their rifles, reverses the flow of gasses from the muzzle. In our version, the brake was an extension of the barrel, increasing its original length by about two inches. Three small ports were drilled into the bore at an angle of 30° to the bore and positioned so that the blast of escaping air was deflected backwards. The blast, would, of course, occur during the brief moment that the pellet was in the extra two inches of barrel. However, the results were disappointing, and probably rightly so in view of the relatively low pressure and volume available at the muzzle of an air rifle. We had hoped that we would have been able to detect a difference in the swing of the suspended rifle in the two conditions, muzzle brake fitted, and no brake. But the readings were all too close to one another to make any discernible difference. Such is the life of investigation!

The so called recoil in air rifles actually caused by the action and reaction of the piston have been purposely ignored up to this point. This is because the jerk caused by the moving parts of the gun is not recoil in the accepted sense of the word, it is, in fact, movement of the gun backwards, followed immediately by a forward movement. The backward motion is started at the instant of piston release because as the spring forces the piston forward it must also force the rest of the gun back. Now in our particular case it took the piston about seventeen milliseconds to travel the length of the cylinder. So at some point before it arrived at the front of the cylinder, it had been violently slowed down by a cusion of air, this deceleration of the piston was imparted to the rest of the gun as a sudden movement forward which, coming so fast upon the previous backward motion, produced the "jerk".

As already mentioned in the chapter on pistons, we found that the magnitude of the jerk was increased when the weight of the piston was increased.

This forward jerk is particularly noticeable when a telescopic sight is mounted on the cylinder of one's air rifle. After a very few shots it will be seen that the telescope has moved back along the cylinder (opposing the forward jerk of the gun). Care must therefore be taken to ensure that the sight is securely pegged to the supports.

CHAPTER EIGHT
LUBRICANT

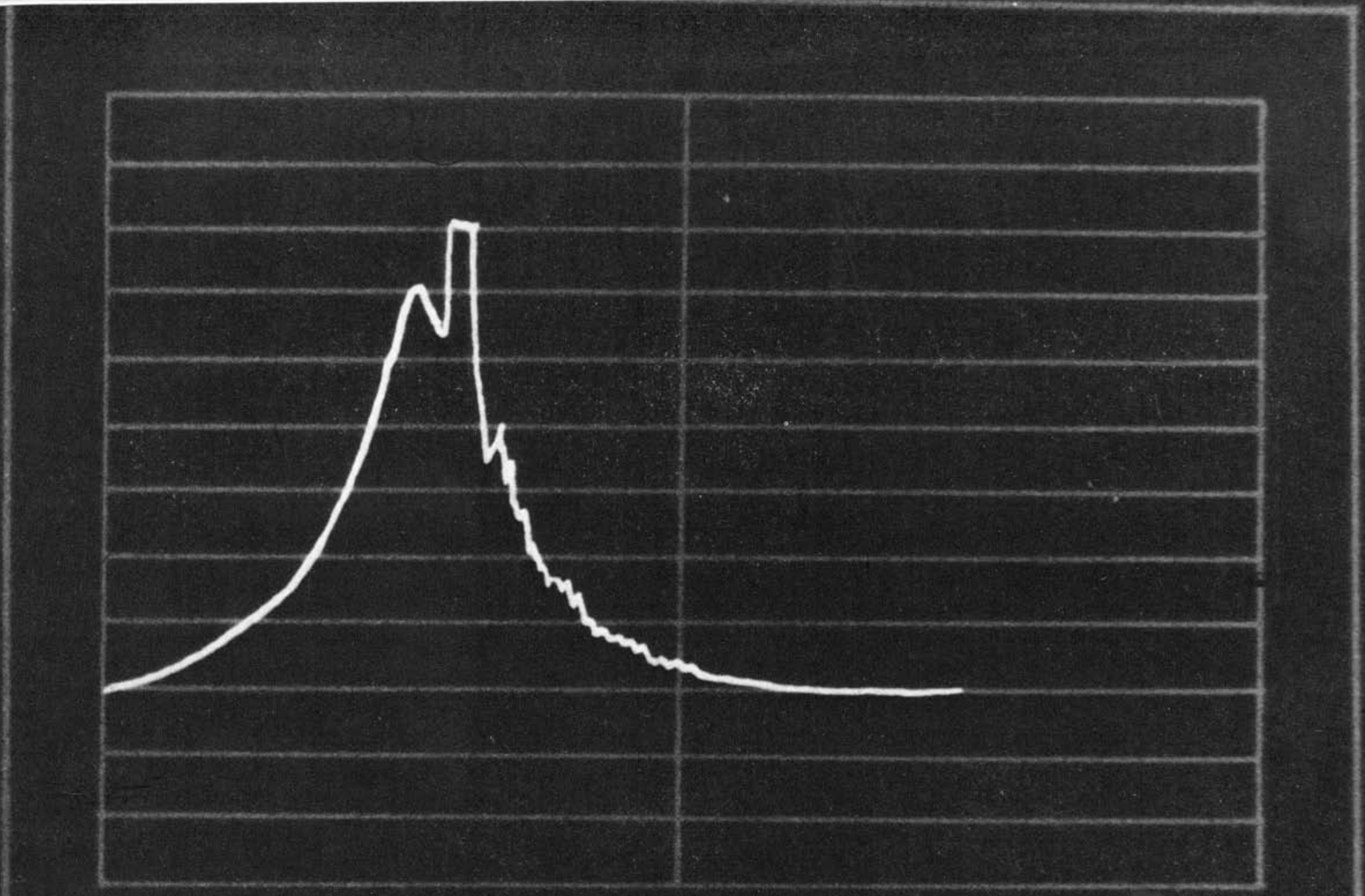
It is vitally important that an air weapon should be correctly lubricated at all the moving parts. It is, however, just as important not to over lubricate as it is to under lubricate. An air rifle should be treated like an instrument, such as a clock. If it is not oiled at all, the parts rub together causing unnecessary wear that ultimately results in total seizure. On the other hand, if it is over oiled, dust and dirt collects on the oil and acts as an abrasive, wearing the mechanism away. Also the dirt laden oil becomes gummy and the whole movement becomes sluggish.

It is worthwhile considering for a moment just why a lubricant is required in any machine. When surfaces slide over one another without there being any form of lubrication between them, they are said to be dry or unlubricated. The resistance to sliding under these conditions is proportional to the force pressing the two surfaces together. Also the material of the surface concerned influences the sliding resistance or friction. This friction is caused by two factors; temporary welding of the high spots of each surface to each other, and the high spots of one surface ploughing through the other.

When surfaces are lubricated, a different set of conditions is introduced, and the friction between them is greatly reduced, it now becomes dependent on the properties of the lubricant rather than the material of the surfaces. The property of the oil which influences the resistance to movement of one surface over another is mainly its viscosity, it is this factor which determines the ease with which the layers of the lubricant slide over their neighbours.

A good lubricant should maintain its viscosity and general nature for a long time. However, under the influence of air, most oils oxidise and deteriorate. This problem must be thoroughly understood by air weapon enthusiasts since most of the lubricaton points on air weapons are open to the atmosphere. The oil should therefore be capable of maintaining its original condition over long periods whilst in contact with the wind and weather. A lubricating grease may be described as oil in a thickening agent, rather in the same way as a sponge holds water. The consistency of the grease depends upon the type of thickening agent used, but again, as with oil, the viscosity depends upon the temperature. Also, greases oxidise at high temperatures or on prolonged exposure to the atmosphere.

The weapon should be lubricated at any point where movement takes place, such as the trigger mechanism and the cocking lever points. There are many brands of oil on the market, sold especially for use on guns. These oils usually contain additives to combat moisture and rust and are all ideal for use on the pins and linkages of air weapons. But the lubricant for the piston should be chosen with great care, since it will be subjected to extremes of pressure and temperature. Most mineral oils, either on their own or contained in a grease, will certainly ignite inside the cylinder as the pressure and temperature build up. Such ignition will produce a shot of unusually high velocity, this phenom-



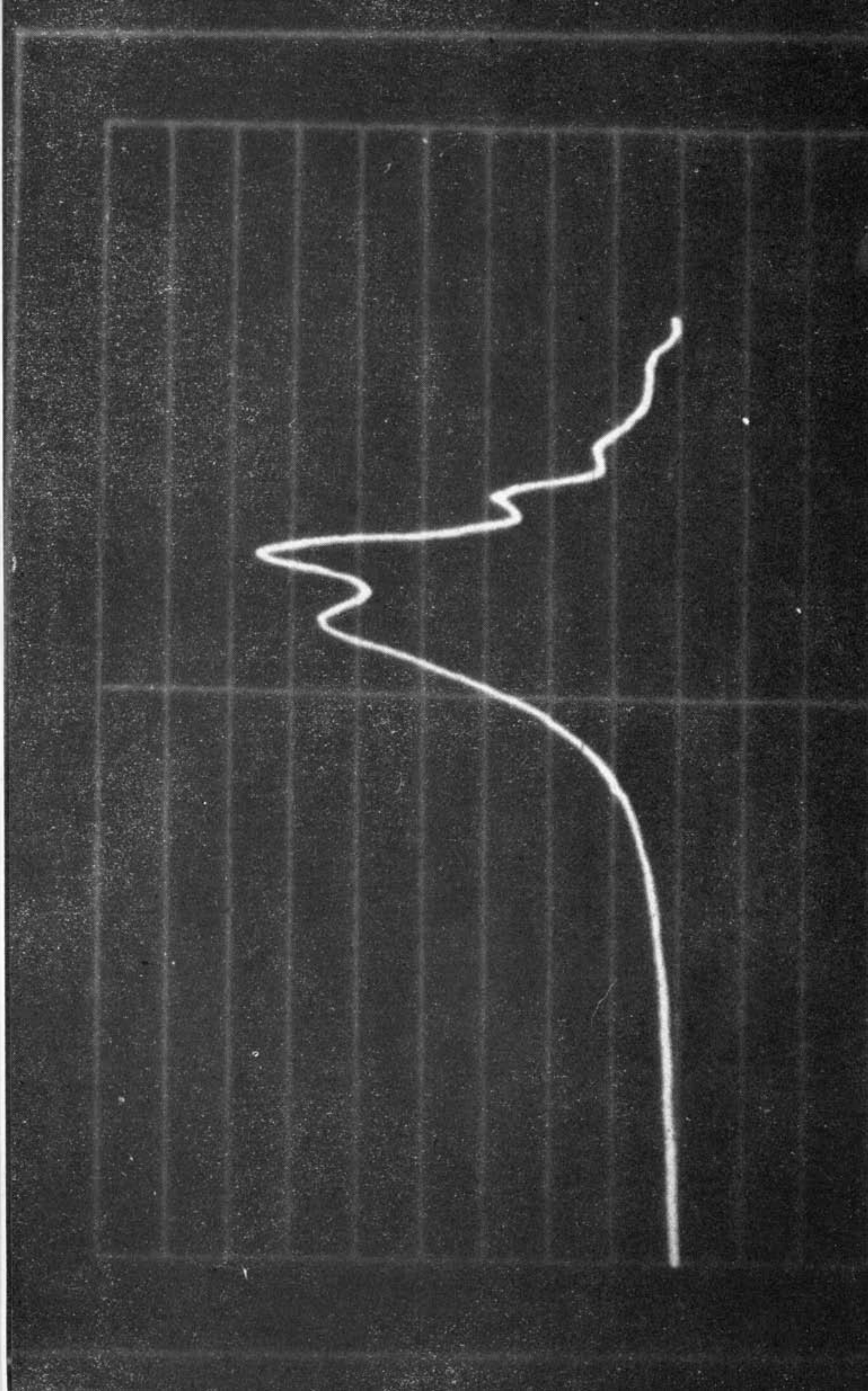
enon in an air rifle is commonly called dieseling. The pressure transients of a diesel shot can be clearly seen in Figs. 8.1 to 8.3. It is interesting to compare these traces with that shown in Fig. 4.1. which is the pressure wave produced by air without any dieseling taking place at all. Figs. 8.1 and 8.2 show the traces of violent dieseling. When explosions of this magnitude occur, the pellet emerges at a terrific velocity, approaching on some occasions the speed of sound. Fig. 8.3, however, shows a normal minor diesel that occurs at almost every shot in an air weapon lubricated with mineral oil. This type of non-violent diesel is difficult to detect without some sort of velocity measuring device, as its makes its presence known only by an increase in velocity relative to the normal shots.

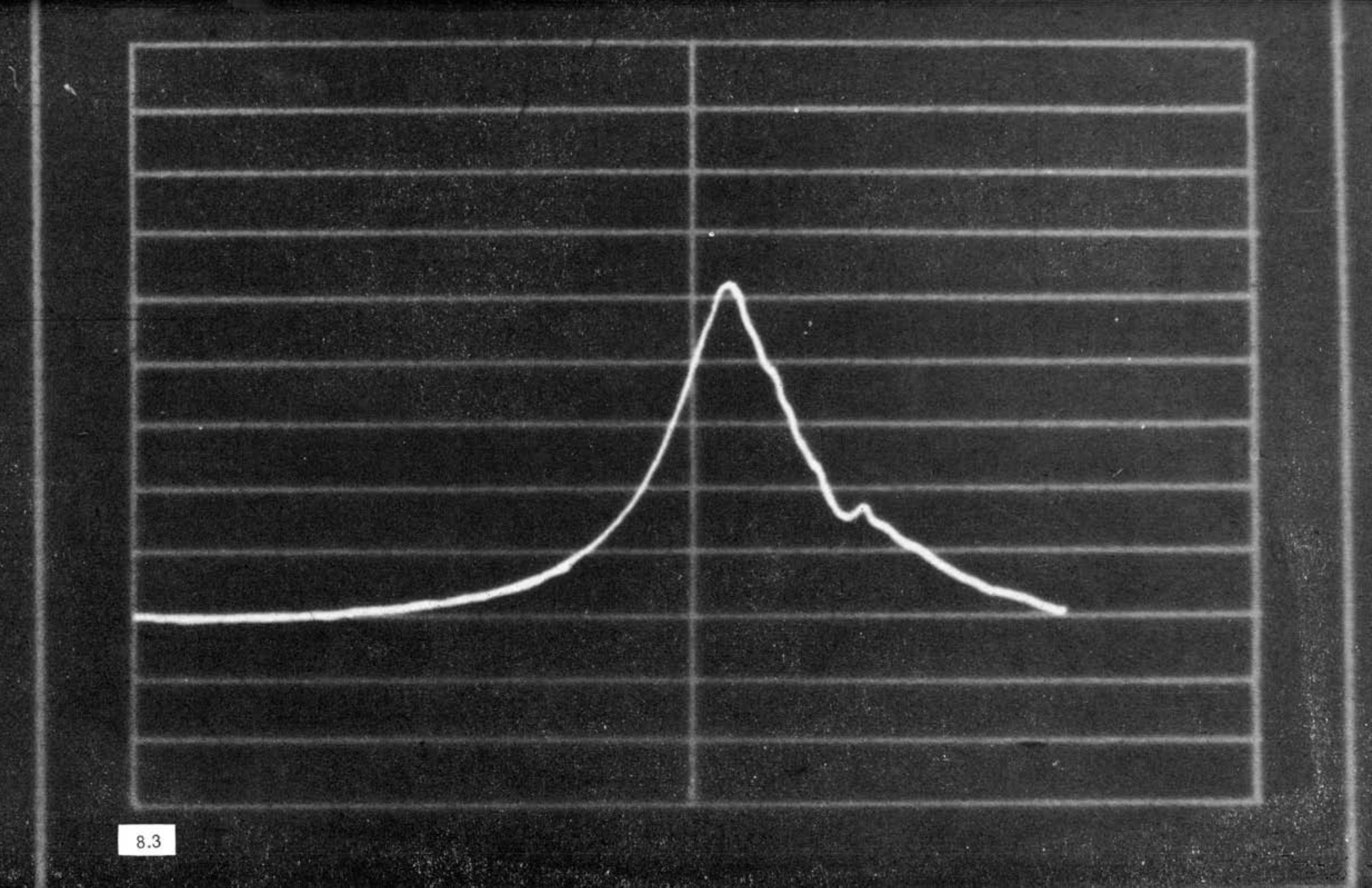
Since the diesel transients occur on the downward side of the pressure waves, the explanation for a diesel shot is thought to be as follows: As the piston comes forward, the pressure and temperature are both raised to a very high figure, but when the piston rebounds, they are dramatically reduced and any oil brought forward by the piston is immediately vaporised by the sudden expansion. Now the temperature at its maximum point is high enough to cause tiny particles of dirt or piston washer to glow red hot. It is these glowing specks or just pure spontaneous combustion, that cause the vaporised oil to burn, producing the surge of pressure on the downward slope of the trace. This burning causes a rise in the pressure behind the pellet which in turn produces a higher velocity than normal. The subsequent spikes on the trace are evidence of reflected shock waves inside the cylinder.

Although a diesel causes a rise in velocity which at first sight might appear to be an advantage, it is in fact, an uncontrollable rise and therefore detrimental to accurate shooting. Even if it were possible to control dieselling, and thereby produce a uniform increase in velocity, there would be little to be gained since the gun would then cease to be an air weapon and would become a firearm. Also, when a rifle diesels, the oil that has been burned in the cylinder forms soot and a gummy residue which reduces the speed of the piston, the remaining sooty particles promoting further diesels.

Illustration opposite
8.1 A violent diesel (a)

Illustration on following pages
8.2 A violent diesel (b)
8.3 A typical diesel





8.3

We wanted to see what really happens inside the cylinder at the moment that a diesel occurs, so we removed the pressure transducer and replaced it with a perspex plug. On firing the "over oiled" gun in a darkened room, we were very satisfied to see the whole plug illuminated by a brilliant white flash, indicating that a diesel has occured. The sound of the gun and chronograph reading both confirmed this observation.

"Molybdenumdisulphide" lubricants are widely used for almost any application one can think of. However, when applied to the piston and cylinder of an air weapon, great care is required in selecting a lubricant in which the MOS_2 is suspended in an oil of sufficiently high flash point to prevent dieseling. The "Moly" one buys for use in the car is just not suitable. The correct grades of MOS_2 are available, but they should be obtained from a dealer who sells them specifically for air guns.

One thing all MOS_2 lubricants do have in common is that they are messy to handle and are, therefore, only suitable for internal surfaces which will not be contacted during normal useage.

Silicone oil on the other hand is very clean and has excellent anti-diesel properties. Having a high flash point, it is an ideal lubricant for leather piston washers but that is the end of its capabilities. It is not a metal to metal lubricant and is, therefore, not suitable for use on the moving parts of the piston or spring.

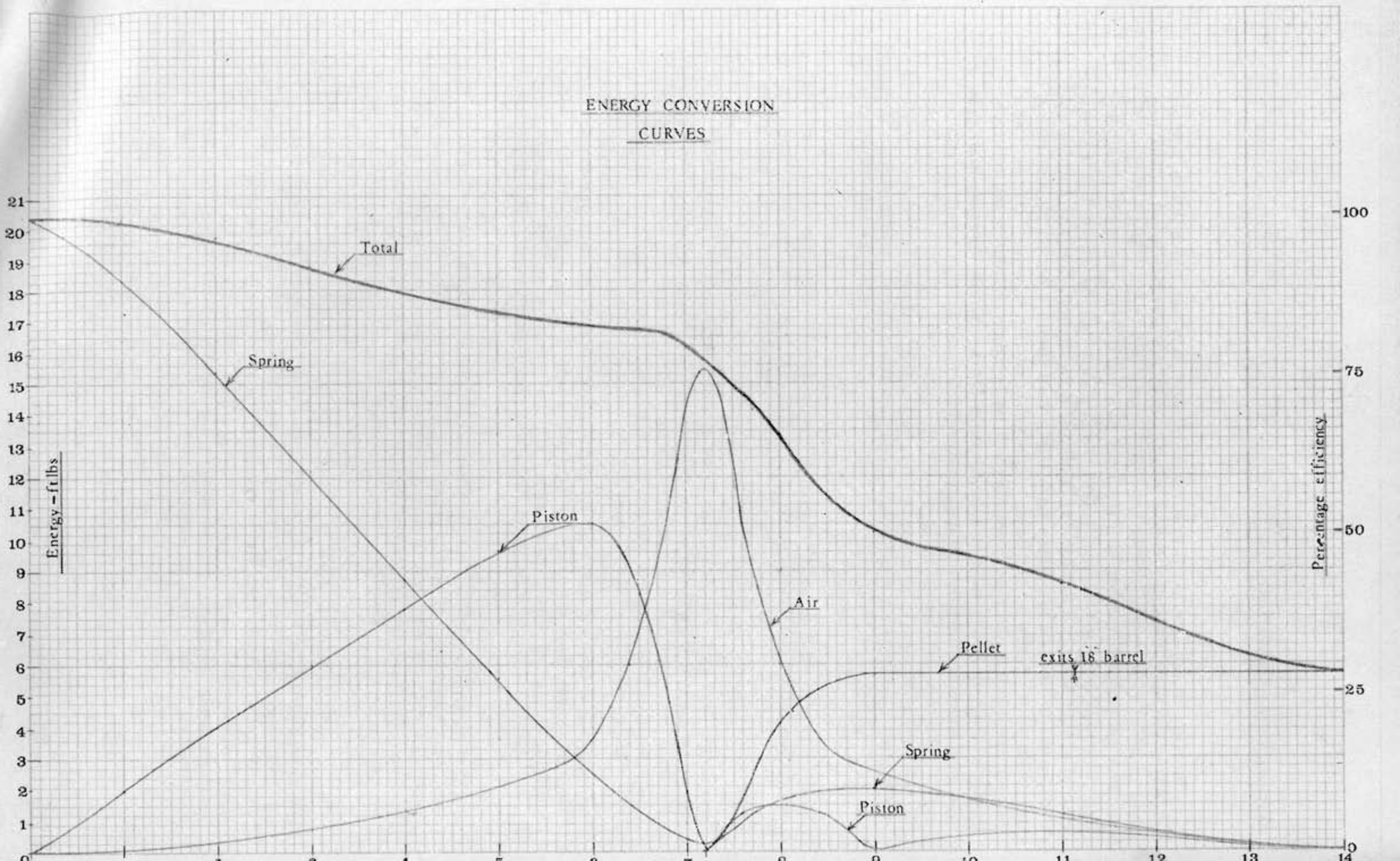
A mixture of molybdenum and silicone oil produces a working compromise but does not always get over the difficulty of retaining the molybdenum powder in suspension in the oil, there being a tendency to separate out. There still remains the difficulty of handling the intensely black substance.

Referring back to the start of this chapter, it is clear that lubrication in some form or another is of fundamental importance. Over the years we have met many enthusiasts who have their own ideas as to the best lubricant or "mix" of lubricants to suit an air rifle. The final choice would seem to be a matter of personal choice, backed up by experience, since every type of common lubricant has its own particular advantages and disadvantages.

Of these many lubricants, few are suitable for use in the cylinder of an air weapon. During our programme of experiments with oils, we came to realise that there are sophisticated synthetic lubricants which are not readily available, but which do meet the requirements of the air gun enthusiast. These synthetic lubricants, manufactured from synthetic oils, generally speaking have a far wider range of application, and when it comes to high pressure and temperature, some of these produce far better results than mineral oils.

Chapter Eight—Lubrication

Working in conjunction with a major oil company, we managed to find an excellent synthetic lubricant that is produced in the form of a gel. This has very good lubricating properties and also a very high flash point. Due to its peculiar gel properties it forms a layer all over the working surfaces producing exceptionally good long life lubrication which clings exactly where it is wanted. Having a high flash point, dieseling is almost non-existent, and any surplus gel that passes in front of the piston performs a very useful function by lubricating the pellet as it passes up the bore. This gel must not, however, be used with any normal mineral oil or its properties will be impaired. This should not be a problem since it fulfills all the requirements for an overall air gun lubricant including anti-rust properties on the metalwork.


ENERGY CONVERSION CURVES
Energy - ft.lbs
Percentage efficiency
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
100
75
50
25
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Total
Spring
Piston
Air
Pellet
exits 18" barrel
Spring
Piston

CHAPTER NINE
EFFICIENCY

The mechanical efficiency of any machine is the ratio of the useful work got out of it, to the work put into it. This ratio is usually expressed as a percentage, thus:

$$\frac{\text{Work output}}{\text{Work input}} \text{ X } 100 = \text{Percentage Efficiency}$$

In this book we have considered the work input of an air rifle to be the amount of energy that is contained in the main spring after the weapon has been cocked, and not the energy that is required to pull the spring into the cocked position. This energy being greater than that in the spring, since there is always a loss through friction at the pivot and slides. We have not made a study of the losses in the mechanical linkage system since manufacturers employ slightly different mechanisms of varying mechanical efficiency.

The work output is the amount of energy contained by the pellet as it leaves the muzzle, this is called the muzzle energy and, like the spring energy is measured in Foot Pounds.

From figures stated in the previous chapters, we can now work out the efficiency of our test weapon:

Energy available from the spring. (Fig. 2.1) = 20.4 Ft. Lbs.
Muzzle velocity, using 14.5 grain pellets = 430 f.p.s.
Hence from Fig. 1.1 the muzzle energy = 5.9 Ft. Lbs.

$$\text{Thus the efficiency} = \frac{5.9}{20.4} \text{ X } 100 = 29\%$$

This figure immediately strikes one as being remarkably low, yet all the rifles that we have tested have produced about the same figure, between 25% and 35%. The variation depends mainly upon the physical dimensions of the weapon.

We shall now closely examine in turn each of the areas of energy loss previously mentioned throughout the book, and also one or two other escape routes. It is the sum of all these losses that reduce the overall efficiency to the low figure of 30%. Fig. 9.1 shows a graph that diagramatically converts the potential energy contained in the cocked spring to the kinetic energy in the flying pellet. This rather complex looking diagram is perhaps the most im-

Illustration opposite
9.1 Energy distribution curves

portant graph in the whole book, since from it can be determined the distribution of energy in the system at any instant during the period of time from the trigger being pulled to the piston finally coming to rest at the end of the cylinder.

Each curve is labelled to show the particular element of the gun that it represents, the thick black line running along the top being the total amount of useful energy in the system at any one moment. The vertical axis shows energy in Foot Pounds, also scaled off, for convenience, on the right hand side in percentage efficiency. The horizontal axis represents the time in milli-seconds (thousandths of a second) from the instant the piston starts moving.

THE SPRING

The main spring is undoubtedly the most efficient part of an air gun since it returns practically all the energy accumulated during the cocking stroke.

From the moment the trigger is pulled, the spring delivers its full complement of stored energy to the piston, it manages to do this very uniformly, thus its energy decrease is represented by the almost straight line from the top of the graph, at which point the spring contained 20.4 Foot pounds, to the lowest point where it contained next to nothing, at this point the piston has compressed the air to peak pressure.

However, when the piston rebounds, the spring is again compressed, by the expanding air, and this amount of energy is wasted. The problems associated with avoiding this energy loss have already been described in the chapter on pistons.

The small losses of energy incurred by the spring are associated with friction since the spring rubs against the sides of the piston and also untwists as it expands. However in a well lubricated weapon these losses are negligible.

THE PISTON

In the chapter on pistons we mentioned that in order to produce a leak-free seal between the piston and the cylinder wall, a piston must produce some friction. It is this friction and therefore, loss of energy, that is the main cause of the Total Energy line falling during the first 7 milli-seconds of the piston's forward stroke, during which time about 3 foot pounds of energy is lost. The frictional part of this loss can, of course, be minimised by the use of a good lubricant.

Turning to the line that represents the energy contained by the piston, it can be seen that the piston gains its energy from the spring at a uniform rate during the first 6 milli-seconds of its travel. Glancing at the "Air" below it, the piston is clearly passing on this energy to the air at a uniform rate. But once the 6 m.s. mark is passed, the piston decelerates rapidly. The rapid slowing down of the piston is caused by the equally rapid build up of air pressure in front of it. This type of compression is called adiabatic and has already been mentioned earlier in the chapter on the air. In that chapter it was mentioned that an adiabatic compression takes place without loss of heat. Now we all understand that if a gas is heated, it expands, and that if it is heated inside a closed container, the pressure will rise since it now cannot expand. In our case we are in a way doing two things at once, first of all, we are raising the pressure of the air by compression, and secondly, we are raising the pressure further through heating it by this same compression. So, both these factors added together, cause the piston to decelerate rapidly, resulting in the downward plunge of the line on the graph. At the same time, the air in the cylinder has undergone an exponential rise in energy, indicated by the sudden upward swing of the "Air" line.

THE AIR

The energetics of the air in an air weapon is, without doubt, an extremely difficult and complex subject to study, one must first of all start out with a knowledge of the basic theory of gases: air is considered to be made up of millions of tiny molecules, all moving about in a random fashion and colliding with each other within the confirmed space of the vessel that contains them, in our case, the cylinder. When the air is compressed, this same number of molecules are pressed into a smaller space, hence the number of collisions between molecules is increased as also are the number of collisions between molecules and the cylinder walls. When the air is compressed by the piston, work is done on the molecules and their velocities are increased, hence their bulk kinetic energy is raised, this addition of energy appears as a rise in temperature. Now as already stated, the compression is adiabatic and no heat energy is lost, therefore, the heat used in raising the temperature of the air during the compression stroke again becomes available to do work during the expansion of the air as it propels the pellet. However, due to certain molecular phenomena, there are attractions between molecules that require energy to overcome them and hence a certain amount is lost in breaking these attractive forces. This loss of energy is attributed to the "non ideality" of the air as a gas, a theoretically "ideal" gas has no internal energy losses. Unfortunately, no such gas exists.

Each individual gas is built up of different molecules, each having their own internal "non-idealities", so we experimented with alternative gases to see if we could find one that was more efficient than air. In each case we sucked a charge of the gas into the cylinder as the gun was cocked, thereby ensuring a completely filled cylinder at an atmospheric pressure for each shot. The oscillographs of the pressure transients of these gases are shown in Figs. 9.2 to 9.7. These should be compared with the trace of the air in Fig. 4.1. Since the piston travel is roughly proportional to time and its speed remained the same throughout the experiment, it can be taken that the area under the curve represents the energy received by that gas. The most efficient gas is, therefore, the one with the largest area below the line. It will be noticed that, in fact, this gas is nitrogen, this is also born out by the fact that the velocity of the pellet projected by this gas is highest (see table below).

Air	**CO_2**	**Argon**	**Butane**	**Freon 22**	**Nitrogen**	**Town Gas**
432	319	412	142	227	429	330
424	304	415	57	193	420	348
430	312	415	107	186	432	353
420	324	422	112	153	434	345
437	308	424	100	170	431	343
433	324	413	106	169	432	345
439	307	420	66	185	437	346
439	313	418	101	148	441	350
425	320	432	56	192	433	352
431	318	418	103	166	438	352
431	**315**	**419**	**95**	**179**	**433**	**346**

The figures at the bottom of each column are the average velocity in feet per second for that column.

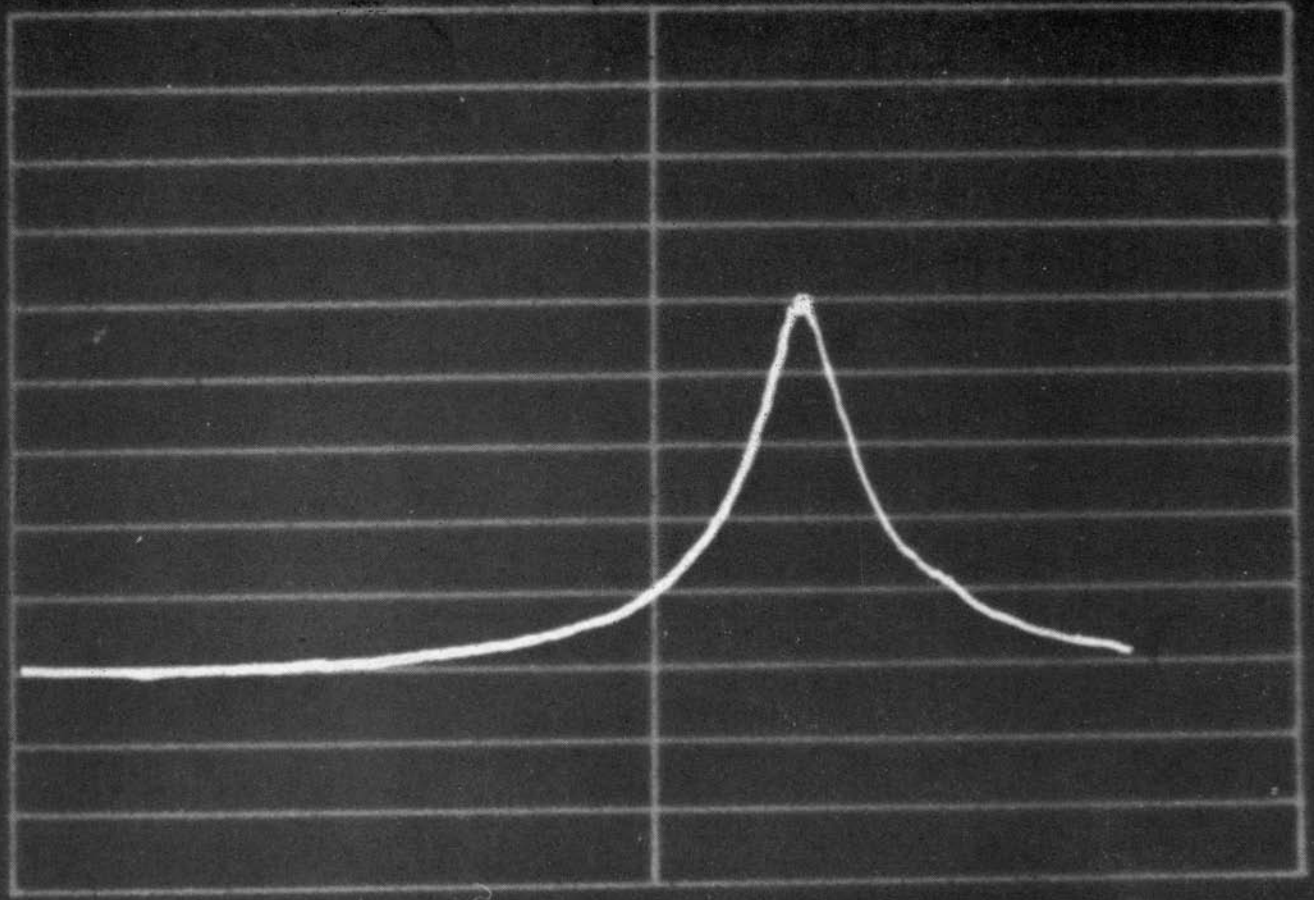
It can be seen from these figures that air and nitrogen are the most efficient gases to use in air weapons of conventional design, it is fortunate, therefore, that air is the gas recommended by air rifle manufacturers ! ! Also, of course, air is two thirds nitrogen in content.

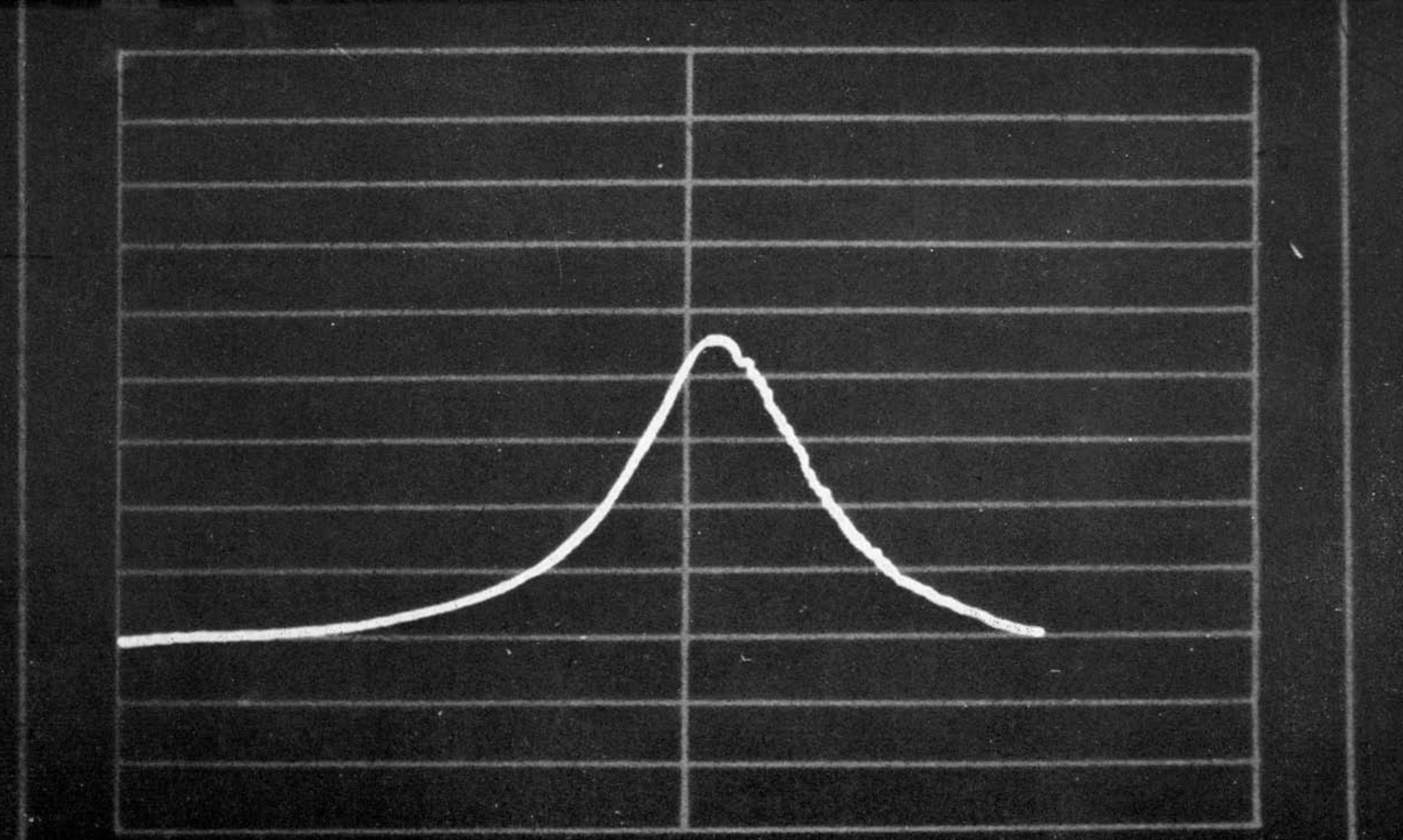
It will have been noticed that such gases as Freon 22 and Butane, produced very strange pressure transients, this is probably due to their unique physical properties, such as viscosity and specific heat capacity ratios, both of which influence the amount of energy stored on compression.

It is often said that an air rifle performs better on a cold day, warm weather robing it of its best. Whilst we were experimenting with the various gases, we decided that the time was ripe to carefully investigate the effect of temperature on the performance of an air gun. We first of all wrapped an electric heating wire around the cylinder and warmed it up, at the same time watching a thermometer that was fixed to the cylinder. Before each shot was fired, the gun was left in the cocked position long enough for the air in the cylinder to attain the same temperature as the rest of the gun. We were surprised to find that the velocity did not change within the normal temperature range expected on a summer day, but on taking the temperature above this point persistent dieselling made it impossible to decide which was the true velocity and which the diesel. At these high temperatures, however, the gun was too hot to hold, so the point is ony of academic interest.

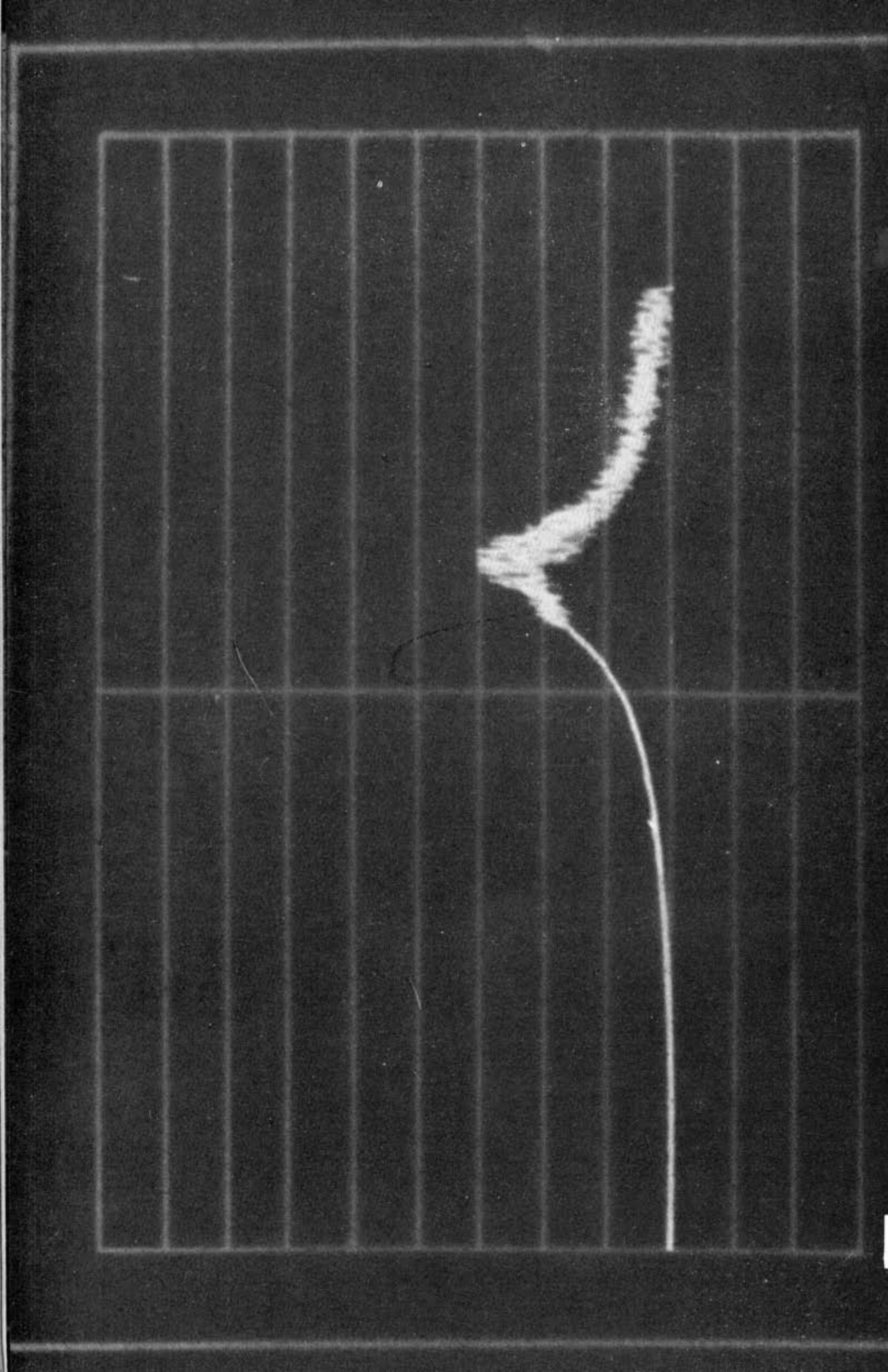
Our next experiment involved cooling the cylinder by injecting refrigerant into a jacket surrounding the cylinder, again we left plenty of time for the air to assume the same low temperature as the rest of the gun. The resulting velocities were very much the same as for the gun at normal temperatures, so we came to the conclusion that temperature, within reasonable margins, has little or no effect upon the internal ballistics of air weapons.

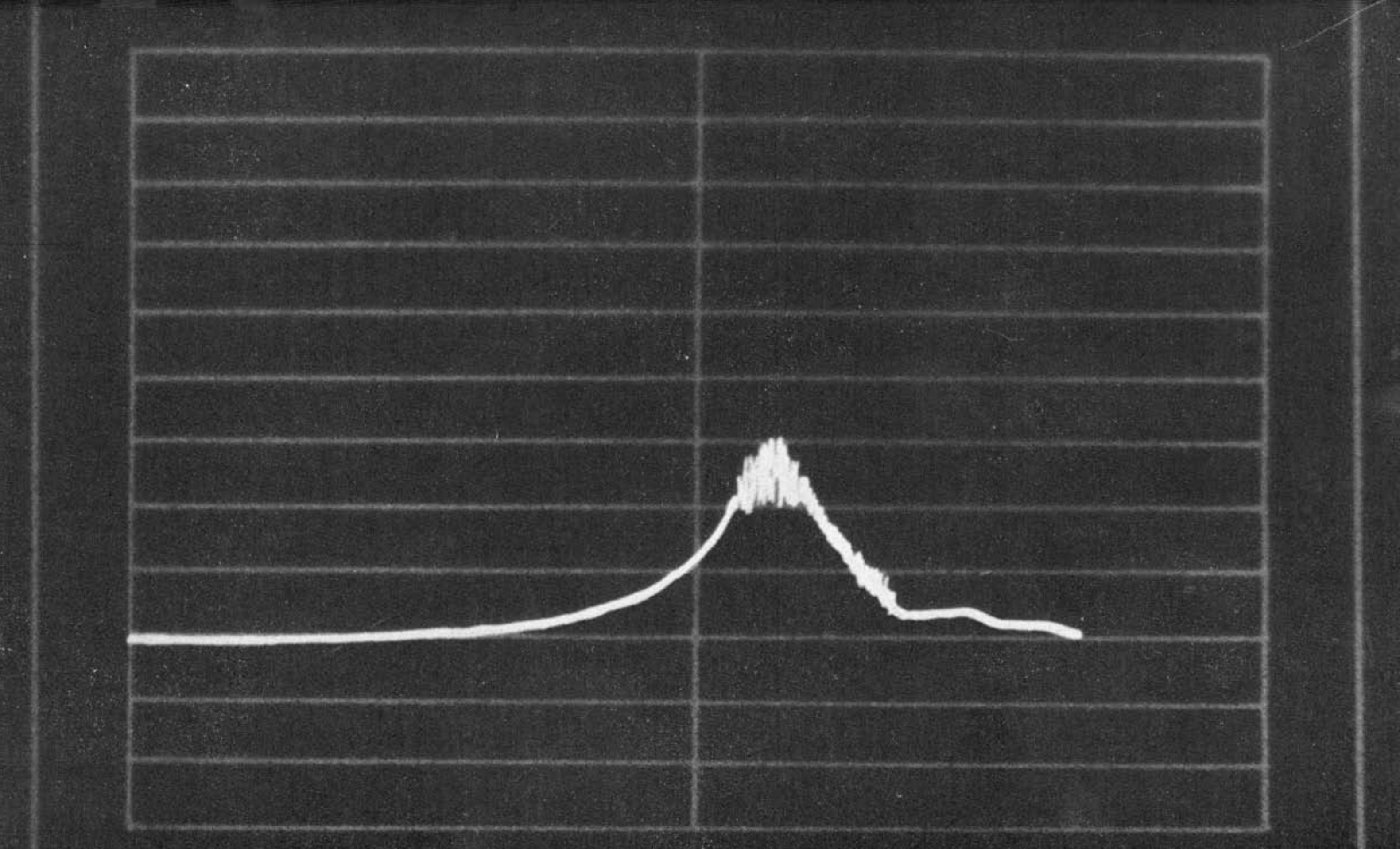
Illustrations on following pages
9.2 Carbon dioxide transient
9.3 Argon transient
9.4 Butane transient
9.5 Freon 22 transient
9.6 Nitrogen transient
9.7 Town gas transient



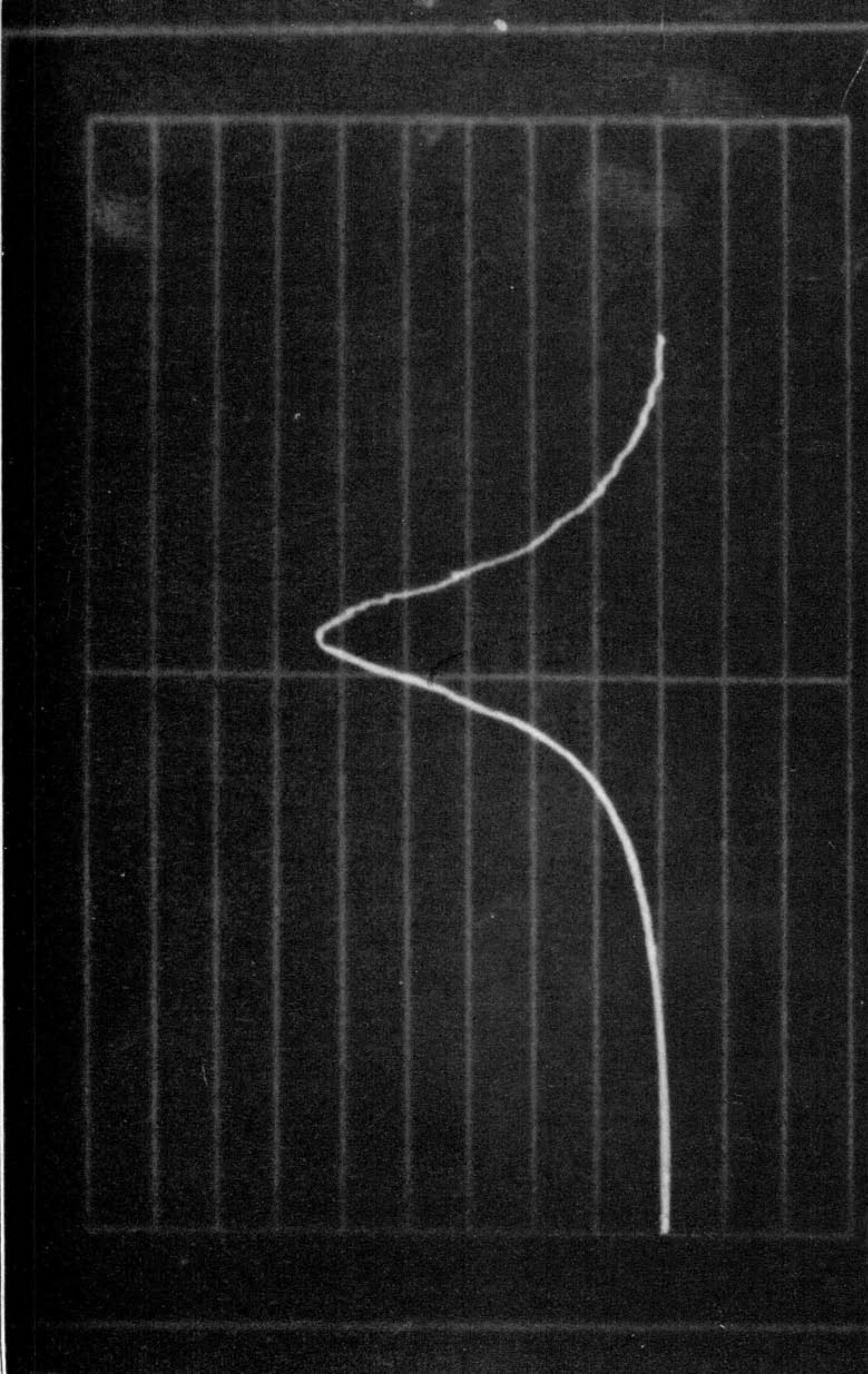


9.3

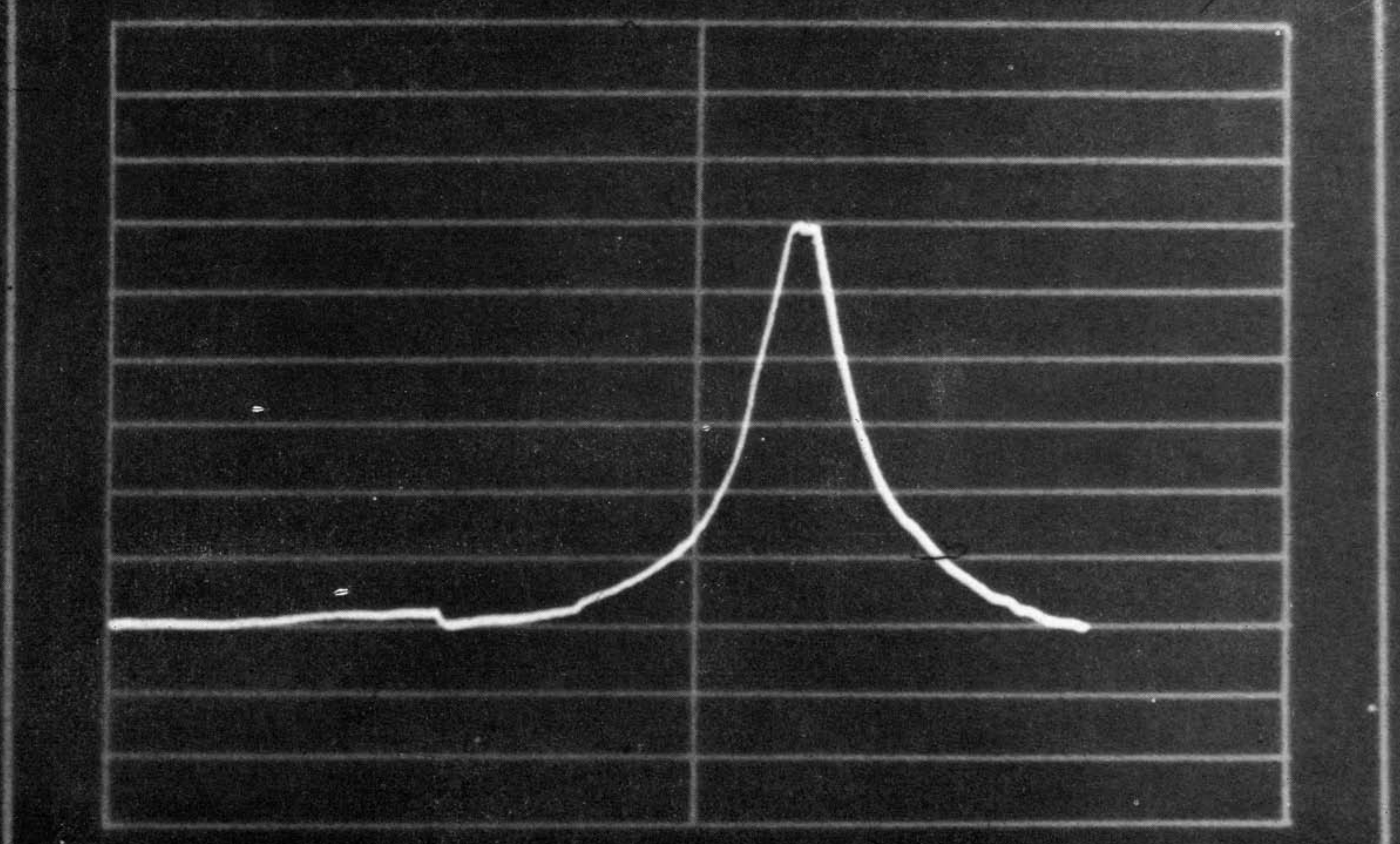




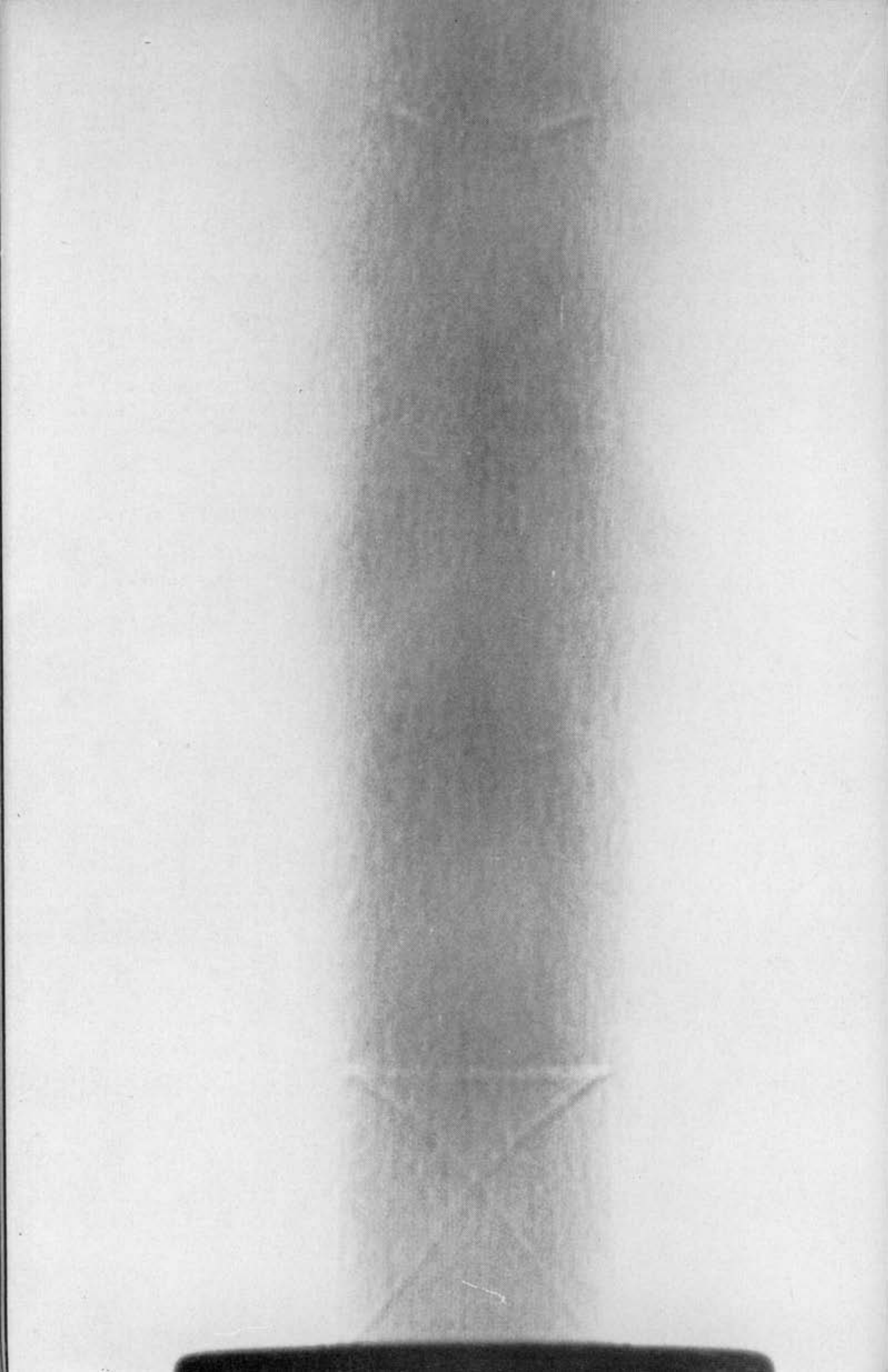
9.5



9.6



9.7



THE TRANSFER PORT

This narrow passage between the cylinder and the pellet can produce losses in efficiency because if it is not properly shaped it will cause air turbulence, also, being of necessity small in diameter, it restricts the flow of air. However, the main loss is due to the shock waves that are set up in the port. Fig. 9.8 shows such a shock wave emerging from the muzzle. The determination of the actual amount of energy lost in the transfer port through shock waves was beyond our capability, but they are certainly one of the major contributors to the violent fall of the Total Energy line between 7.2 and 9 milliseconds in the energy diagram, Fig. 9.1.

THE BARREL

There is only one significant loss of efficiency that can occur here and that is the shape of the breech as mentioned in Chapter 6. This must be correct so that the pellet receives the maximum acceleration from the pressure that it holds back. There are other negligible items, such as the friction in the barrel and the energy to rotate the pellet by the rifling but we have proved these to be so small that they can be ignored.

The efficiency of an air weapon can, however, be somewhat increased by using a larger diameter projectile:

Calibre	Weight (grains)	Velocity	Muzzle Energy	Efficiency
0.177	7.4	507	4.2	23%
0.22	14.0	405	5.1	28%
0.25	19.0	354	5.3	29%

All the above readings were taken with an energy input of 18 foot pounds.

This gain in efficiency can be seen to be true by applying the following equations:

FORCE = PRESSURE x AREA

FORCE X DISTANCE = PRESSURE x AREA x DISTANCE

Now Force x Distance is units or Energy, thus:

ENERGY = PRESSURE x DISTANCE x AREA

Illustration opposite

9.8 Shock waves emerging from the muzzle

This simple formula shows that from purely mechanical considerations, the muzzle energy is a function of the average pressure in the barrel, the base area of the pellet and the length of the barrel.

Further consideration shows that if the cylinder pressure remains constant, which it must, unless the power of the spring is altered, the average barrel pressure will fall as the barrel length increases. This situation is further aggravated by choking in the transfer port, and is the main reason for the pellet ceasing to accelerate after the first 6 inches or so of barrel (see Fig. 6.1).

We can, therefore, say that the pressure is "approximately" inversely proportional to the distance of the pellet up the barrel.

i.e.

$$\text{PRESSURE} \propto \frac{1}{\text{DISTANCE}} \quad \text{(approximately)}$$

or

$$\text{PRESSURE} \times \text{DISTANCE} = \text{'CONSTANT'}$$

Thus, from the above formula, substituting for Pressure x Distance:

$$\underline{\text{ENERGY} \propto \text{AREA}}$$

That is for a given energy input, the muzzle energy is a function of the calibre only, and is largely independent of the pellet weight.

THE TOTAL

So summing up, we have five functions in the operation of our air weapon that contribute to its inefficiency, making the overall energy loss a mighty 71% of the input energy. A quick glance at Fig. 9.1 tells us that we cannot blame any one factor, since such a complex interchange of energy takes place that the effective efficiency of each function varies from millisecond to millisecond.

However, certain broad conclusions may be drawn:

The energy transfer from the spring via the piston to the air is very efficient: Approximately 76%

The transfer of energy from the air via the transfer port to the pellet, however, is not so good: Approximately 37% of the above 76%, that is 29% of the total input energy, as already stated.

We may now break down the energy losses of each function, very approximately, by considering the energy remaining in them, (and therefore "lost") at the instant the pellet leaves the barrel.

ENERGY BALANCE AT THE MUZZLE

FUNCTION	ENERGY	
The Spring:— After rebounding	lost	6%
The Piston:— After rebounding and now coming forward to rest at the cylinder end	lost	3%
The Air:— Some pressure remaining, the "puff" which follows the pellet	lost	5%
The Transfer Port:— Mainly shock waves	lost	23%
Friction	lost	34%
The pellet:— As Kinetic energy	contains	29%
TOTAL		100%

CHAPTER TEN
CHRONOGRAPHS

The chronograph is to ballistics what the speedometer is to motoring. Without it one cannot compare machines or evulate the results of experiments.

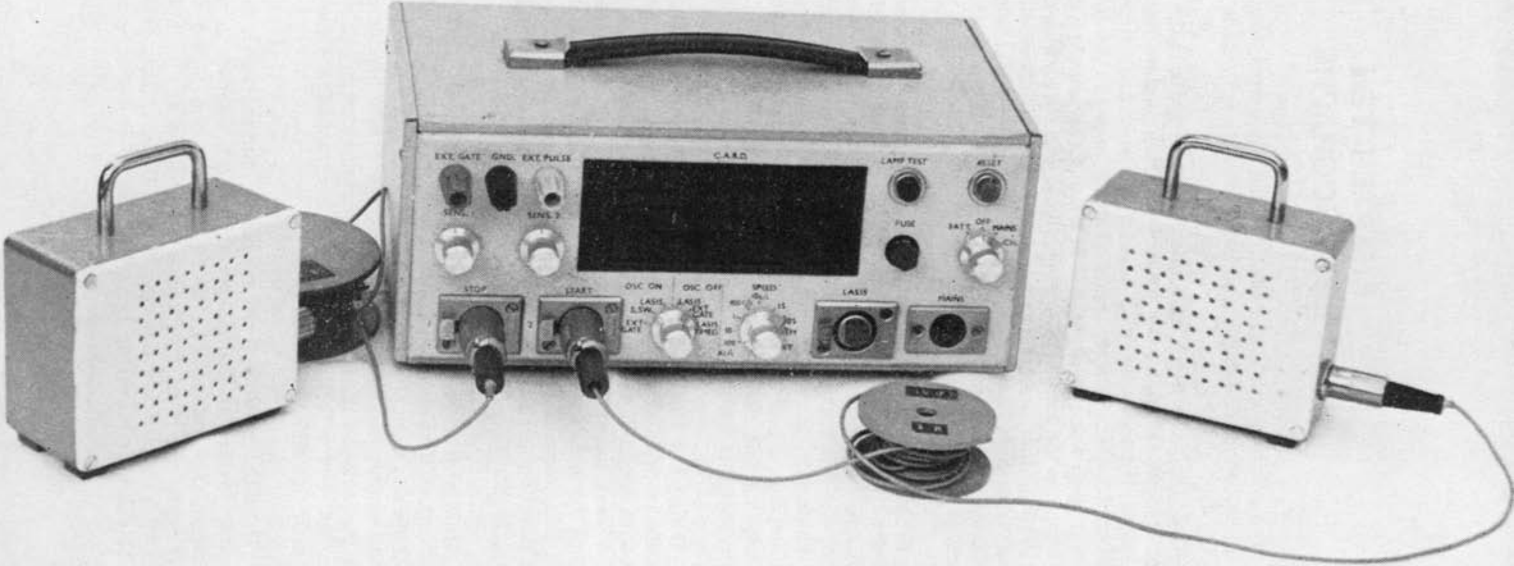
Over the years there have been many attempts to devise a simple means of velocity comparison for air weapons. Each system has relied on measuring the depth of penetration of a pellet into a substance such as putty or sheets of cardboard. Unfortunately, each of these methods produce results that do not depend upon velocity alone, this is because penetration is largely influenced by the shape of the front of the projectile. For instance, a round nosed pellet will penetrate further than a flat faced "wadcutter", all other factors remaining the same. Our own favourite means of comparing penetration is to shoot into old telephone directories, but the results are at best purely of interest and have little practical value.

Probably the first person to devise a scientific device for the measurement of velocity was Benjamin Robins, who, in 1742, patented a Ballistic Pendulum. With this instrument he was able, for the first time, to measure accurately the velocity of his experimental bullets. This instrument, one must imagine, laid the foundation for the scientific study of ballistics; it was the only practical solution to the problem of measuring the speed of bullets for about 100 years. Throughout this period much work was done in efforts to devise an electric instrument that would be more accurate and easier to use than the pendulum.

During the 1890's, a system was developed by le Boulenge that used two screens or grids of wire that the bullet cut during its flight. The rupture of the first wire released a long weight which fell under the action of gravity; when the bullet traversed the second screen, a spring loaded knife made a mark on the side of the weight at a distance proportional to the time elapsed during the fall. With this information, and knowing the distance apart of the two screens, it was possible to calculate the velocity of the bullet during its flight between the two screens.

Brilliant though the early instruments were, they all suffered from the same problems of time delay in the moving parts. All sorts of ingenious ideas were embodied to cancel out their effects but one must presume that these only added to unreliability in the final stystem. With the coming of the radio valve and the science of electronics, the chronograph became a very precise instrument, and with the invention of the transistor it became possible to have portability as well as accuracy.

The chief problem of any electronic chronograph is to be found in establishing the position of the pellet in its flight relative to a fixed point or more correctly, two fixed points, those at either end of the flight distance. In the early types we have mentioned the position of the bullet was registered by causing it to break an electric circuit. Unfortunately, this system is not entirely suitable for air rifles, the energy absorbed in breaking the wire may slow the


EXT. GATE
GND.
EXT. PULSE
C.A.R.D.
LAMP TEST
RESET
SENS. 1
SENS. 2
FUSE
BATT.
OFF
MAINS
STOP
START
OSC ON
OSC OFF
SPEED
LASIS
MAINS

pellet by an unacceptable amount. Also it is a very frustrating business replacing the screen after every shot.

The system that is used in military establishments depends on the projectile interfering with the light falling on a photo cell. The light source being either sunlight, when working outside or fluorescent tubes when indoors. The whole unit being called a "Sky Screen". Unfortunately, the cost of such equipment is prohibitive in the air weapon field.

We bypassed this problem by the use of microphones. After doing a little investigation, we found that as the pellet emerges from the barrel, it is accompanied by a very energetic sound wave.

We picked up this wave with a microphone placed near the muzzle, the resulting electrical pulse started the chronograph. In the same manner when the pellet arrived at the other end of its measured distance, another microphone registered the noise as it flattened itself against the pellet catcher.

Figure 10.1 shows our chronograph with the two microphones and cable spools. This instrument can be used either on the domestic mains supply or on its own internal rechargeable battery. The heart of the system is a crystal controlled pulse generator which produces exactly one hundred thousand pulses per second. These pulses are fed into the electronic switch which is controlled by the microphones and from there into the pulse counter and display panel. The display on this unit, being similar to that on an office desk calculator, is very easy to read even when out on the open shooting range.

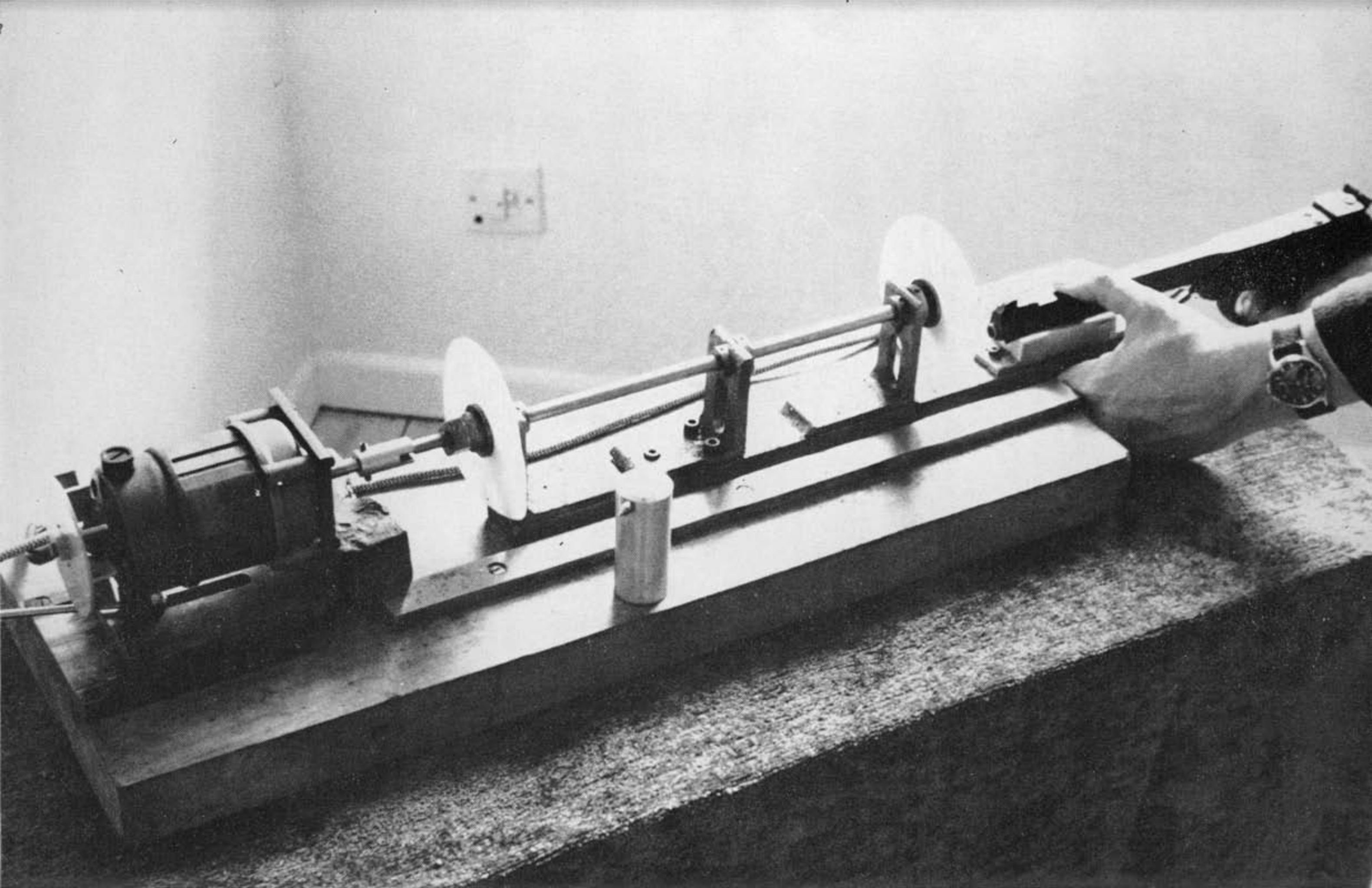
The complete sequence of events that takes place when taking a velocity reading is that the first microphone registers the pellet emerging from the gun and switches the pulses from the internal oscillator into the counter. As soon as the pellet arrives at the other end of its flight, the pulse from the second microphone stops the flow of pulses. The display can now be read and the speed of the pellet calculated from the following formula:

$$V = \frac{S \times n}{C}$$

Where

V = Velocity in feet per second.
S = Distance in feet between Microphones.
n = Pulse rate of counter.
C = Displayed count.

Illustration opposite
10.1 Our electronic chronograph



Incredible though it may seem, once the first microphone has registered the pellet, all the subsequent switching and countering is carried out at approximately the speed of light, that is, 186411 miles per second. Just about instantaneous when compared with the average speed of a pellet at about 600 feet per second.

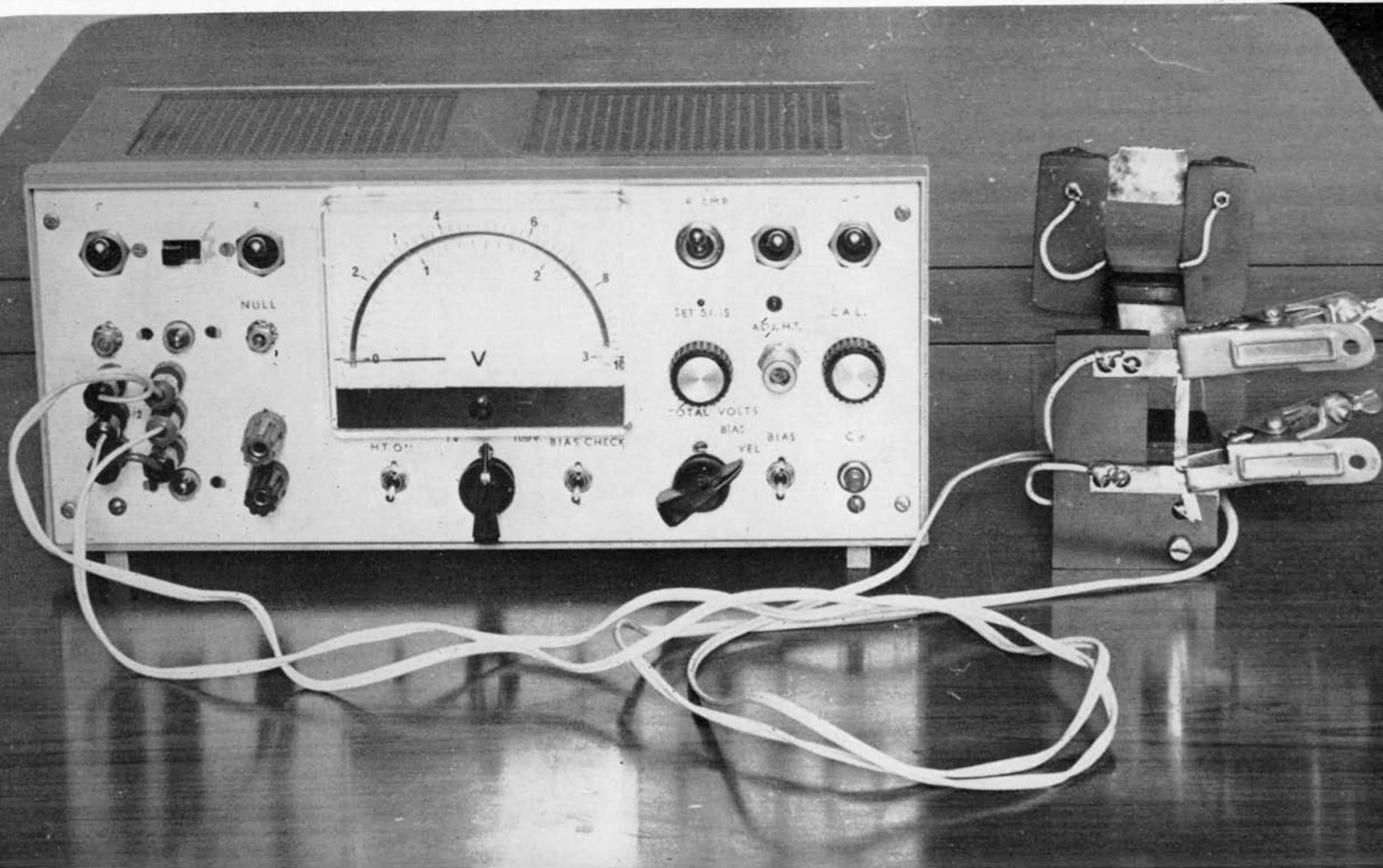
The great beauty of modern chronos is that they can register the position of the projectile without any interferance with its velocity. At the same time, they can measure the time interval to a very small fraction of a second. In our case this amounts to one hundred thousandths of a second, but it would be no more difficult to measure to a millionth of a second. Also. there is no need to replace any screen after each shot, the only thing that has to be done before the next shot is fired is to remember to press the reset button so that the display is cancelled on the electronic switching reset.

A very interesting mechanical chronograph has been developed by Mr. R. Jeffery of Cornwall. A picture of this instrument is shown in Fig. 10.2. Two paper discs are spaced exactly one foot apart and are rotated at high speed by an electric motor. The shot is fired parallel to the drive shaft so that each disc is penetrated in turn by the pellet. Since the discs are rotating there will be an angular displacement between the two pellet holes, this displacement is measured and the velocity calculated, knowing the speed of the motor. In this case 1200 revs. per minute has been found to give enough displacement to make an accurate reading possible. Obviously it is important to check that the motor speed does not vary because the instrument depends upon this for its accuracy. It has been suggested that the pellet might be deflected by the rotation of the first disc and, therefore, give a false reading as it penetrated the second. Experiments carried out to check this point, however, have shown that the effect is negligible as a percentage of the final reading. This instrument demonstrates clearly what can be done by an ingenious experimenter with plenty of perseverance and without the expenditure of a large sum of money.

Returning to electronic instruments, another system has been employed by Mr. A. Terman of Edinburgh. This is rather more complicated than those that have been described so far, it relies upon the fact that an electrical capacitor charges up through a resistance at a known rate dependent on time, provided that the supply voltage remains constant. The complete equipment is shown in Fig. 10.3.

The pellet is fired along the bar, first breaking a small piece of aluminium foil, held by bulldog clips, then at the other end it knocks a piece of steel away from two magnets. The foil and the magnets are exactly one foot apart and they determine the distance over which the reading is taken. Electrically

Illustration opposite
10.2 Mr. Jeffery's chronograph


NULL
V
SET BIAS
ADJ. H.T.
CAL.
TOTAL VOLTS
H.T. ON
BIAS CHECK
BIAS
VEL
BIAS

speaking, the sequence of events is that as soon as the aluminium is broken, a capacitor starts to charge, then as the steel is removed, the charge is discontinued.

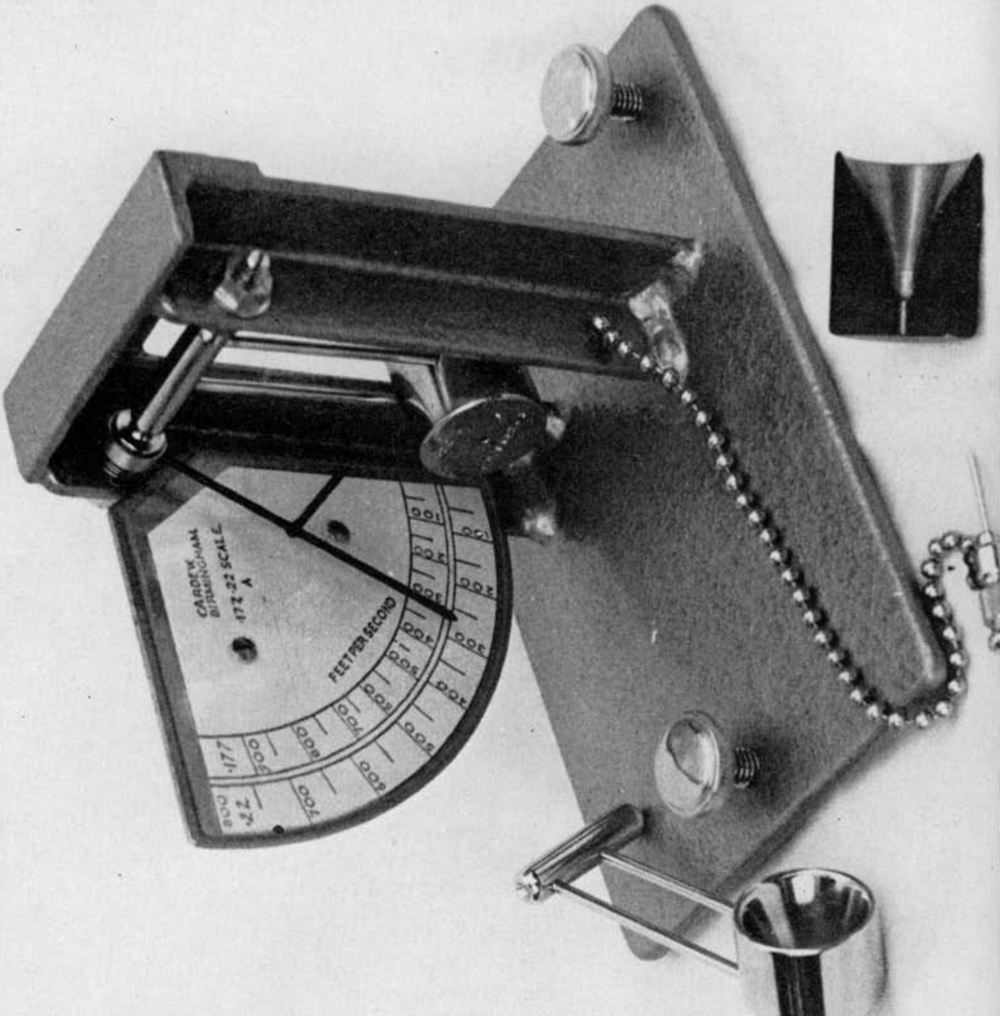
The meter is then switched across the capacitor and the voltage that has built up in it is read. From a calculated chart it is then possible to determine exactly how long the charge period lasted and from this the velocity can be arrived at since the charge period is exactly the same as the time of flight between the foil and the steel. In practice it is not quite so simple, and quite sophisticated electronics are required to ensure that the voltage remains stable and that the meter does not impose any load on the capacitor when the voltage is read. Again it could be argued that a load is imposed upon the pellet as it breaks the foil and again as the steel is knocked away from the magnets, but tests have shown that the retarding effect of these obstacles is negligible.

Now returning to that very cheap and simplest of all velocity measuring instruments, the ballistic pendulum. The "Robins" pendulum set the path to the investigation of the flight of bullets. It was a heavily built instrument that carried a flat faced bob against which the bullet was fired. As the pendulum swung back under the force of the impact, it dragged a tape with it, the amount of tape that was pulled past a fixed point indicated how far the pendulum had travelled and from this the velocity of the bullet could be calculated.

One can imagine the scene as the musket ball hit the bob, hot lead would fly everywhere occasionally cutting the tape as it flew. The very fact that the ball broke up and the fragments flew about indicates that not all the energy was being absorbed by the pendulum, and therefore, a low reading was indicated.

In our early experiments with a pendulum scaled down for air weapons, we soon realised that a lot of energy was being expended in particles of lead flying off the flat face of the pendulum bob as the pellet disintegrated. Clearly a bob shape had to be devised that would catch the pellet and absorb as much of the kinetic energy as possible without making the bob difficult to hit, after one or two unsuccessful designs, we finally came up with the idea that a funnel shape might be the answer, not only to the energy problem, but also to another snag inherent in ballistic pendulums; if the pendulum bob has a flat face, then a shot that strikes above the centre will give a low reading and one that strikes low will produce a high reading. This variation from the true velocity caused by high or low shots on a flat faced bob was great enough to make the whole instrument unacceptable as a tool for serious investigations.

Illustration opposite
10.3 Mr. Terman's chronograph


CARDEW
BIRMINGHAM
.177-.22 SCALE
A
FEET PER SECOND
.177
.22
100
200
300
400
500
600
700
800

The new funnel shape guides the pellet into a small pocket where it can transfer as much energy as possible to the bob, at the same time the pellet is prevented from breaking up and dissipating energy in flying fragments. Since the funnel has tapered sides, any high or low shot is automatically returned to the centre and the error is corrected. We were so pleased with the accuracy of the new shape that we went to the trouble of registering the design at the Patent Office.

We have sectioned a bob so that the shape can be seen with the actual pendulum in Fig. 10.4.

The calibration of a ballistic pendulum is based upon the projectile having a given mass, if the mass is changed, then the velocity scale must also be adjusted, to suit the new weight, or alternatively, the mass of the bob may be altered, provided that the centre of gravity remains in the same place. This is not as easy as it sounds, since the weight of the bob is a very critical factor in the accuracy of the whole instrument. When we adopted the ballistic pendulum for air weapons, we intended an instrument that would cater for both 0.177 and .22 calibre rifles, but an average 0.22 pellet is twice the weight of a 0.177 and this variation produced many problems when trying to compromise bob weights. We were finally forced to have separate scales and bobs for each calibre in order to obtain a useful range of velocities on the scales.

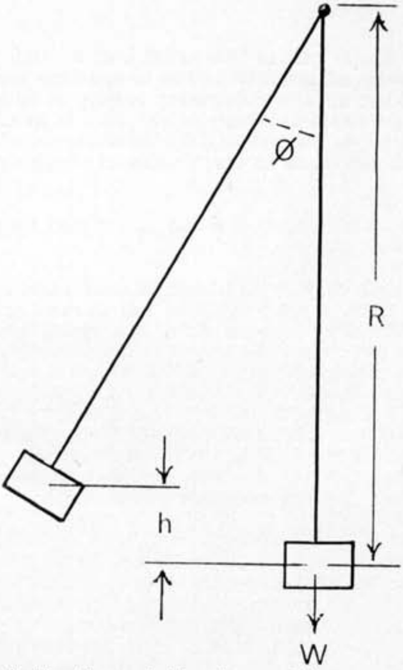
The tape on the Robins instrument has been replaced on our model by a pointer that is carried across a scale by the bob on its backward swing, it then stays in that position, held by a slight amount of friction at its mounting. Although this amount of friction is very small, we always advise the user to preset the pointer about 100 f.p.s. below the expected reading, this ensures that the effect of the friction is minimised. After all, one wants to get the highest reading possible, without actually cheating! Another little dodge that we find to be helpful is lightly greasing the inside of the bob, this makes the removal of each pellet much easier and greatly reduces frustration.

One great advantage of a pendulum is that if one is interested in the energy contained in a pellet rather than its velocity, one can read this energy directly by fitting a scale that is calibrated in foot pounds.

We have often been asked by mathematically minded air weapon enthusiasts to explain the theory behind the pendulum, so we will set it out again for those who may be interested.

Starting off with the symbols that will be used in the calculations, we have:
g = Acceleration due to gravity. Ft./sec./sec.
V = Velocity of pellet. Ft./sec.
w = Weight of pellet. Lbs.
W = Weight of pendulum. Lbs.
h = Height of Swing. Ft.
R = Radius from pivot to C of G of bob. Ft.
$\varnothing$ = Angle of swing.
m = Mass of pellet.
M = Mass of pendulum.
U = Velocity of pendulum.

Illustration opposite
10.4 The Ballistic pendulum



Now a pellet, as it flies through the air, contains momentum by virtue of its mass and velocity.

Thus, the pellets momentum = mV.

If the pellet is now fired into the pendulum, then by the law of conservation of momentum:

$$mV = (m + M)\,U$$

Since gravity is constant, the above may be re-written in terms of weight:

$$wV = (w + W)\,U \qquad \text{or} \qquad U = \frac{wV}{(w + W)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Now the combined energy of the moving parts, that is the pellet plus the pendulum, is given by:

$$E = \tfrac{1}{2}\,(M + m)\,U^2$$

Or

$$E = \frac{(w + W)\,U^2}{2g}$$

Thus, substituting for U from equation (1)

$$E = \frac{(w + W)}{2g} \quad \frac{(wV)^2}{(w + W)^2}$$

Or

$$E = \frac{w^2 \; V^2}{2g \; (w + W)} \qquad \text{.....................(2)}$$

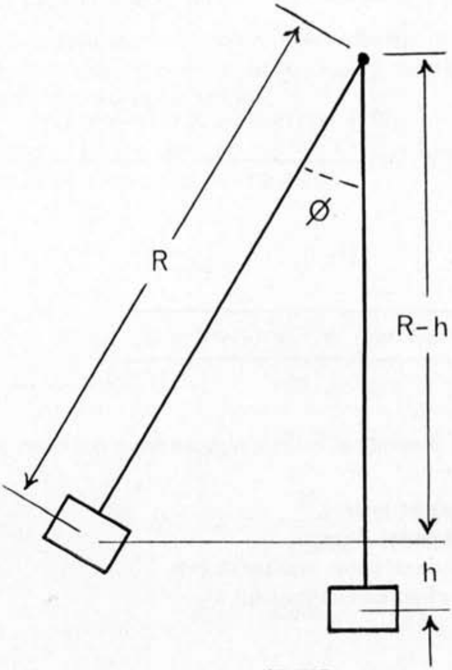
Now since the pendulum swings up to a height h it contains the potential energy of:

$$E = (w + W)\, h \qquad \text{.....................(3)}$$

We now have two equations for the energy contained in the pendulum because equations (1) and (2) are both concerned with the same energy.

So:

$$E = \frac{w^2 \; V^2}{2g \; (w + W)} \quad = \quad (W + w)h \qquad \text{........................(4)}$$



The basic equations now being complete, we could substitute values for W and w. Direct measurement of h would make the calculation of V^2 possible, and hence the velocity of the pellet. But it would be impractical to measure h with any degree of accuracy, the measurement of the angle of swing is far easier, from this the value of h may be calculated:

$$\text{Since } \cos \varnothing = \frac{R - h}{R}$$

$$\text{then } h = R - R \cos \varnothing$$

$$\text{or } h = R (1 - \cos \varnothing)$$

Thus, substituting for h in equation (4):

$$E = \frac{w^2 V^2}{2g\ (w + W)} = (W + w)\ R\ (1 - \cos \varnothing)$$

or:

$$V^2 = \frac{(W + w)\ (W + w)\ 2g\ R\ (1 - \cos \varnothing)}{w^2}$$

Thus:

$$V = \sqrt{\frac{2\ g\ R\ (W + w)^2 \times (1 - \cos \varnothing)}{w^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This is only a theoretical value since we have not been able to account for any losses such as:

(1) Heat at pellet impact.
(2) Sound at pellet impact.
(3) Deformation of pellet and pendulum.
(4) Rotation of pendulum through Ø.
(5) Friction.

Now, if by practical tests, using a chronograph to check the velocity, we raise the pendulum through a measured angle Ø degrees, these losses could be eliminated. Further, since g, R. W, w, are all constants for given pendulum, we can sum them all together and call them K.

So from (5)

$$V = \sqrt{\frac{2\,g\,R\,(W + w)^2}{w^2}} \times \sqrt{1 - \text{Cos } \varnothing}$$

$$V = K \sqrt{1 - \text{Cos } \varnothing} \qquad \dots\dots\dots\dots\dots\dots\dots \quad (6)$$

A very important fact that must now be noted and that is that K is the velociy necessary to produce a pendulum swing of 90°, since cos $\varnothing = 0$ when $\varnothing = 90^\circ$.

This figure K is of great value when a new pendulum and scale are being prepared to suit some special gun or pellet. Using this figure K it s relatively simple to determine the new scale range.

Thus, if a pellet of known velocity, say 500 f.p.s. is fired at a pendulum and produces a swing of 50°, then from equation (6):

$$K = \frac{V}{\sqrt{1 - \text{Cos } \varnothing}}$$

or:

$$= \frac{500}{\sqrt{1 - \text{Cos } 50^\circ}}$$

$$K = \frac{500}{\sqrt{1 - 0.6428}}$$

$$K = 836.6$$

Thus, with that particular weight of pendulum, a shot fired at 836.6 f.p.s. would produce a swing of 90°. And from this, any other angle for a given velocity can be found by transposing equation (6) into:

$$\text{Cos } \varnothing = 1 - \left(\frac{V}{K}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots(7)$$

Thus, for example, a pellet travelling with a velocity of 400 f.p.s. would produce a swing through:

$$\text{Cos } \varnothing = 1 - \left(\frac{400}{836.58}\right)^2$$

$$\text{Cos } \varnothing = 0.52186$$

$$\varnothing = 58.5^\circ$$

We have now arrived at two separate equations (5) and (6) either of which will solve our problems, the difference between the two being that the second has got a built-in allowance for the various factors that were unknown in the first. Although definite values were stated for both W and R in equation (5) in practical terms it is not easy to arrive at these figures since, in the case of W, it is only the weight of the actual bob that is being considered, and the bob must have some sort of suspension, which in turn must have weight. In the case of R it is not easy to arrive at an accurate position for the C of G and any slight error in this area will have an effect on the final calibration.

In our view the theoretical equation is only of value in the initial stages of the construction of pendulum, but, thereafter,, the second equation should be used. This depends upon the availability of some other way of determining the velocity of the first shot in order to arrive at the constant K.

ADDITIONAL DATA

A DICTIONARY OF TERMS USED THROUGHOUT THE BOOK

Acceleration:
The rate of change in velocity. In feet per second, $ft.s^{-2}$.

Adiabatic (compression or expansion):
The process during which no heat transfer occurs.

Efficiency:
The ratio of energy output to energy input.

Energy:
The capacity for doing work. In foot pounds, ft. lbs.

Flash point:
The lowest temperature at which the vapour from a liquid fuel will ignite on application to a flame.

Force:
That which moves or tends to move a body, or which changes or tends to change the motoin of a body. Same units as weight.

Ideal gas:
A gas which obeys the gas laws of Boyle and Charles, precisely.

Internal energy:
The internal energy of a gas is the energy contained by that gas by virtue of the motion of the molecules within the gas.

Kinetic Energy:
The energy of bulk motion of a body.

Mass:
The quantity of matter which a body contains. In pounds or grains.

Momentum:
The product of mass and velocity.

Velocity:
The rate of change of position. In feet per second, fts^{-1}. or fps.

Weight:
This is mass acted upon by the acceleration due to gravity. Thus weight is mass x 32.16. In pounds force lbs. f. (more commonly referred to in pounds lbs. not differentiating between mass and weight).

Work done:
The product of force x distance through which it acts. In foot pounds ft. lbs.

SUMMARY OF FORMULAE

Adiabatic expansion or compression:

$$P_1 V^n_1 = P_2 V^n_2$$

$$T_1 V_1^{n-1} = T_2 V_2^{n-1}$$

P_1 = First pressure

P_2 = Second pressure

V_1 = First volume

V_2 = Second volume

T_1 = First temperature

T_2 = Second temperature

n = Ratio of specific heat capacities, for air = 1.408

Efficiency

$$\frac{\text{Output energy}}{\text{Input energy}} \times 100\% = \text{Percentage efficiency}$$

Kinetic energy:

$$E = \tfrac{1}{2}MV^2$$

$$E = \frac{wV^2}{2g}$$

E = Kinetic energy

M = Mass

V = Velocity

w = Weight of body in lbs.

g = Acceleration due to gravity, $32.16\ \text{ft.s}^{-2}$

E = Energy in ft. lbs.

If w is in grains, divide by 7000 to convert to pounds.

Work done on or by a gas when its volume changes from V_1 to V_2.—

$$\text{Work done} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

CONVERSION FACTORS — METRIC TO ENGLISH/ENGLISH TO METRIC

1 Inch = 25.4 millimetres. 1 mm = 0.03937 inches
1 Foot = 0.3048 metres. 1 metre = 3.2808 feet
1 Foot pound = 0.1383 Kilogramme metres = 1.3558 Joules
1 Kilogramme metre = 7.233 foot pounds
1 Joule = 0.7376 foot pounds
1 Grain = 0.06479 grammes
1 Gramme = 15.4324 grains
1 Pound = 0.4536 Kilogrammes
1 Kilogramme = 2.2046 pounds
1 Foot per second = 0.6818 miles per hour
1 Mile per hour = 1.4667 per second
1 Atmosphere = 14.22 pounds per square inch

Some prefix often used before units

mega (M) 1 000 000	10^6	
kilo (k) 1 000	10^3	
milli (m) 0.001	10^{-3}	$\frac{1}{1000}$
micro (μ) 0.000 001	10^{-6}	$\frac{1}{1\ 000\ 000}$

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