F. WANKEL

ROTARY PISTON MACHINES

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Classification of Design Principles for Engines, Pumps and Compressors

Felix Wankel

Translated and Edited by
R. F. Ansdale, A.M.I.Mech.E., M.S.A.E.

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Preface

Many years of work on sealing problems and rotating piston machine layouts, including rotary internal combustion engines, has focused attention on the need to classify this type of mechanism.
This classification is, therefore, intended to provide a comprehensive perspective of this vast and complex subject as well as a measure of guidance in the technicalities and unavoidable terminology. It should also facilitate a sensible sifting of the enormous amount of published information including the extraordinarily numerous patent specifications, so that individual designs may be readily traced.
Preparatory work was started in 1938 at the WVW – the Wankel Experimental Establishment – in Lindau, Germany, where it was continued in 1944. Unfortunately, all these preliminary studies were lost or destroyed in the aftermath of war, moreover the process of sorting out and classifying had to be resumed secretly in the privacy of home. Despite these formidable obstacles it was found possible to devise principles according to which the machines may be grouped relative to the movement imposed upon the centres of gravity of the respective moving parts; this facilitated the discovery of many new basic configurations. It was not until 1951 that these activities could be resumed openly in the newly formed TES – Technische Entwicklungsstelle – Engineers Wilhelm Hotzel, August Jarchow, Dankwart Eiermann and Walter Rogg, as well as draughtsmen Elisabeth Schwartz and Johanna Wolf, must be singled out for their valuable contributions.
Dipl.-Ing. Wolf Dieter Bensinger's valuable advice and suggestions with regard to this manuscript and his technical summary contained in the conclusion are much appreciated.
Similarly Professor Othmar Baier enriched the contents of this book by his meticulous and constructive checking, especially of the kinematic aspects of the various designs.
Because there is such a bewildering variety of rotary piston machines, few of which have been appraised in any detail, it was thought opportune to subject them to closer analysis, scrutinise their movements, bearing and drive arrangements, including the sealing systems of many already known and new designs. Gradually the general pattern of this classification began to emerge and many configurations fell simply into their logical places. Many gaps in the general pattern, thus revealed, could be filled in with designs which until then could not be placed with certainty; other gaps still remain because it proved impossible to obtain either patent specifications or published data. However, their characteristics could be deduced by reference to the adjacent configurations.
In this way and by repeated arranging and rearranging of the diagrammatic sketches into groups and categories there developed an almost natural, though partly incomplete, classification of rotary piston machines. This classification will need bringing up to date from time to time in much the same way as additions have been

made to the classifications of species and chemical elements. The Publisher and the author will, therefore, gratefully receive every suggestion for improving this book, adding other as yet unknown rotary piston engines and if attention is drawn to any errors which may have been included despite the greatest care.

Summer 1963 Felix Wankel

Publishers' Note

An International Conference of experts, held after the book had been printed, recommended that the term Kämmeingriff would be more appropriately translated as 'intermeshing engagement' than as 'cam engagement'.
On this basis 'cam engagement' should be read as 'intermeshing engagement' and $\overline{C}$ as $\overline{I}$ throughout the book.

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Translator's notes

It should perhaps be explained that the extensive use of the term 'machine' is due to the fact that rotary-piston machines incorporate all manner of pumps, blowers, and compressors as well as steam engines and two and four-stroke rotary internal combustion engines.
It is important to differentiate between 'Rotary-piston machines' (ROPIMA), which is a term used for the whole family of machines, and 'Rotating-piston machine' (ROM) which describes a particular configuration; the other two types are Single (SIM) and Planetary-rotation (PLM) machines.
After careful consideration the term 'engaging' was adopted to describe the act of forming variable volume chambers between two or more components which rotate relative to each other. Indeed, this action is very similar in some designs to the meshing of two gears although the resemblance may not be quite so clear in other designs.
Finally it should be emphasised that the English edition to of this book contains various modifications and additions which take into account observations and results obtained during the continuing research. These alterations were included after consultation and at the request of the author.

1. Introduction

While reciprocating piston engines can be made in few different basic configurations, an almost infinite variety of rotary piston arrangements is feasible. Indeed, the possibilities are so unlimited that they have tended to hamper the realisation of rotary piston machines, through focusing attention on the search for new and better types of rotary piston units rather than on fundamentals such as adequate arrangements for sealing the working chambers.
Existing systems devised for the classification of rotary piston machines are not sufficiently comprehensive and often incorporate inconsistencies which make them generally unsatisfactory. However, the growing number of such machines urgently demands some system of classification so that inventors can readily place their designs and quickly determine whether a particular idea is really new or whether it is already known. In time, such a system can be of invaluable assistance to patent experts in placing an invention in its appropriate category. Finally, and significantly, it can ease the problem of communication between development engineers and between the inventor and the development engineers.
The following classification of rotating piston machines is the result of a very careful and comprehensive study. Every important proposal and invention is, as far as available data will allow, carefully evaluated. By analysing first of all the characteristics of any particular design it is possible to place it in its appropriate group, relative to already known inventions, and to assess its features accordingly. It is,

of course, anticipated that many of the blank spaces on the classification sheets will become occupied in the course of time while others are doomed to remain blank since the required configurations and characteristics cannot be realised in practice.

2. Definition of parts

A piston machine is a mechanism which contains a working chamber, surrounded by solid walls for the accommodation of liquid or gaseous working media. The chamber volume is varied by the relative movement of at least one part of the chamber wall with respect to the rest while maintaining efficient sealing contact. The moving part transmits energy either to or from the working medium and is here called a piston because it is best known as such from the reciprocating piston engine. If it forms part of a rotary mechanism it is defined as a rotor or rotary piston (RP). It is called a piston or rotor irrespective of its shape.

The containing chamber walls, which are not working parts, may also move relative to the piston or rotor in order to facilitate balancing or to escape from the path of the working parts. This kind of part is called a sealing component (SC) and is distinguished by the fact that although it is exposed to the working pressures it cannot exert any torque.

In the following sketches the power transmitting parts are coloured red, sealing components blue and stationary housing parts black. In some piston machines the function of output and sealing components may be performed by two components in alternative sequence. These components are logically coloured violet – a mixture of blue and red. Output or crankshafts are coloured yellow and sealing elements green.

A fixed centre of gravity of a moving part, or the centre of a shaft in a fixed bearing, is shown as a white point.

An orbiting centre of a moving part or the centre of a crank pin or eccentric is coloured blue, red or violet respectively depending on the coding colour of the engaging or meshing component (output or sealing member).

3. Power output members with reciprocating or unidirectional motion

Piston machines are divided into two major groups according to the behaviour of the c.g. of the power output member and the method of chamber volume variation. That is, machines with reciprocating motion and those with unidirectional motion.

To the first category belong the reciprocating piston machines, in which the c.g. of the power transmitting part (piston) moves to and fro in a straight line or, if the cylinder is allowed to swing about a fixed centre, in a circular arc. In the case of a

pendulum piston arrangement the piston c. g. is allowed to oscillate in a circular arc or, in another embodiment, oscillates about its own c. g.
To the second category belong the rotary piston machines of which the c. g. of the power component (piston) moves at uniform or non-uniform speed in one direction along a circular or differently shaped closed path. The power component (piston) may also rotate at uniform or non-uniform velocity about its c. g.

4. Types of reciprocating piston and rotary piston machines

The working chamber volume of reciprocating machines (REM) may be varied as follows:

1 a) A piston may have straight linear motion in a stationary cylinder. Alternatively, the piston may be stationary and the cylinder may move to and fro.
A cover or cylinder head is usually firmly attached to the cylinder but may, if convenient, be replaced by a slide or rotary valve. Furthermore, a second piston may replace the cylinder head or closing valve, as in certain opposed piston machines.
1 b) Straight cylinders may be given a to and fro motion – as on some oscillating cylinder steam engines – alternatively the cylinder sleeve may reciprocate or rotate for the purpose of opening and closing of the inlet and exhaust ports – as in sleeve valve engines.

2. Pendulum-piston arrangements, although no longer produced as heat engines, are also possible; the cylinders of these units have either a round or square section bore arranged as a circular arc along which the appropriately shaped piston oscillates. Vane type manually operated pumps with these characteristics are, for example, still being made by the Allweiler Company.

3. Apart from the types indicated in 1 a and 1 b – with actual cylinders – and those indicated in 2 – with partly rotating components – it is feasible to obtain reciprocating piston movement by way of a suitable screw thread but this type of machine has apparently been ignored.

Arrangements in which the power component or working part of a chamber (piston) is connected to other moving parts, do not seem to be very numerous. In old types of reciprocating piston machines, which featured no rotating power output member, chains or connecting rods usually linked the piston to a beam. However, in reciprocating piston machines with a rotating output shaft the connecting rod is linked either directly to the crankshaft or indirectly by way of a beam, bell-crank or reversing gear. There are very few instances in which a reciprocating piston acts either directly upon suitable cams (or swashplates) or indirectly by way of interposed rollers. Finally, there are the free-piston engines in which the energy is transmitted directly by the piston to another working medium.
The familiar layout of reciprocating piston engines – in line, V, horizontally opposed,

radial etc. – has been derived from the type of engine in which the piston is constrained to move in a straight line.
By comparison, far many more different basic configurations of rotary piston machines (ROPIMA) are possible, of which, moreover, each individual type may be executed in many and greatly differing versions. Their systematic analysis and relative evaluation as practical propositions is complicated by two factors:

1) The vast number of different designs.
2) The physicists and designers who have undertaken this task but have failed to pay sufficient attention to the varying motions of the relevant components and the motion of their centres of gravity in particular.

This is easily understood in relation to the history of the technical sciences. It was, for example, quite immaterial to the ponderous machines, produced up to the end of the 19th Century, whether a part moved at variable or at uniform velocity about or with its centre of gravity. The avoidance or control of inertia rose to decisive importance as speeds increased. Consequently greater significance was attached to mechanisms in which the moving parts ran at uniform velocities, that is at a steady pace about their centres of gravity or whose respective centres of gravity moved at uniform velocities.
In the field of electrical engineering the constant speed electric motor soon superseded the reciprocating motor which had been derived from coil type bell actuating devices variously said to have been invented by John Maraud, J. P. Wagner, Neff or Page. With the internal combustion engine, however, uniform velocity of all moving parts has been the prerogative of the gas-turbine. While the positive displacement engines heralded the age of the internal combustion engines until recently it was impossible to avoid variable velocities – linear or rotary – in this type of machine. When classifying rotary piston machines it is however essential to evaluate the means provided for avoiding or controlling any inertia forces so that their development as potential high speed units is possible.
From the following classification of rotary piston machines, it quickly becomes evident that inventors and designers can derive clear guidance from the emphasis placed on what happens to the various centres of gravity of a particular design. In addition, kinematic relationships of superficially very different rotary piston machine designs will become apparent.

5. Single rotation — Planetary rotation — and Rotating Piston Machines

Rotary piston machines (ROPIMA) may be divided into three distinct groups according to the mode of motion imparted to the centres of gravity of the moving parts: (SIM) single rotation machines, (PLM) planetary rotation machines and (ROM) rotating piston machines.

SIM

In single rotation machines all the moving parts rotate at uniform angular velocities about their own centres of gravity. These machines may be completely balanced, hence there are no dynamic loads on the bearings. Single rotation machines are, therefore, eminently suitable for the highest rotational speeds.

PLM

All moving parts of planetary rotation machines rotate at constant angular velocities in addition to which at least one of the moving members performs a constant planetary rotation – in a circular or near circular path – about a fixed point, besides turning about its own centre of gravity. Both these superimposed velocities are, of course, constant angular velocities. Although the orbiting parts may be completely balanced, the forces due to their moving masses must affect the loads imposed on at least one bearing.

The suitability of this type of machine for medium to high rotational speeds depends entirely upon the ability of the bearing arrangement to cope with the unavoidable centrifugal forces.

ROM

Rotating piston machines may be subdivided into those units which display characteristics similar to the single rotation machines (SROM) or show similar characteristics to planetary rotation machines (PROM). Furthermore, the power output member (piston or rotor) of a single rotation design may move at variable angular velocity or, in the case of planetary-rotation arrangements, the power output member may orbit at variable angular velocity. It may possess only a single mode of rotation or it may also revolve at variable angular velocity about its own centre of gravity. In cases where the power output member revolves at a constant speed only, at least one other part of the chamber forming arrangement must rotate or orbit at variable angular velocity or reciprocate.

This type of machine will be found suitable only for low to medium speeds.

5.1 Relative positions of the axes of rotation

All rotary piston machines belong to one or other of three large groups which are distinguished from each other by the relative positions of their axes of rotation.

1. In parallel axis rotary piston (ROPIMA) machines the axes are spaced as for two meshing spur gears. The axes of parallel and external axis (ROPIMA) machines are therefore arranged in the same way as the axes of two external teeth spur gears, while for parallel and internal axis (ROPIMA) machines the axes are arranged as those of an external spur gear meshing with the internal teeth of a ring gear. This leaves the special case in which the two axes coincide; this configuration is to be called a central axis machine. Furthermore it is possible that several axis arrangements were incorporated in a particular design. For instance, it is possible to design parallel-external axis and parallel-internal axis machines.

Engagement or relative movement of the working chamber forming components of rotary piston machines may be performed in exactly the same manner as the meshing of straight spur, helical or spiral tooth gears.

2. In yet another category of ROPIMA machines the axes are inclined relative to each other. They contain an included angle as do the axes of two bevel gears. Furthermore, ROPIMA machines with inclined axes may be divided into those with internal and those with external axes; the components which form the variable volume working chamber may move relative to each other as do spur, helical and spiral toothed gears.

3. The axes of intersecting axis ROPIMA machines have been arranged in the manner of skew or spiral type gears. This group may also be subdivided into intersecting external axis and internal axis ROPIMA machines.
Due to the fact that the volume variations take place in space rather than in convenient planes it is extremely difficult to draw or make diagrammatic sketches of inclined or intersecting axis machines. This type of machine is not considered in further detail in this book. Logical evaluation and classification must, if necessary, be reserved for a future occasion.

5.2 Methods of engagement (or relative motion of parts which form the working chamber)

There are five simple (pure) and several complex methods whereby the machine configurations of the first double groups as well as of parallel axis machines can form variable volume working chambers.
The variable volume may be formed due to cam action $\overline{\text{(C)}}$ * in compliance with the laws and ratios of meshing gears. Consequently the outer and slower revolving rotor of internal axis machines, which rely upon cam action, must have at least one tooth more than the inner faster rotating member. However, the laws of power transmitting gears do not necessarily apply to components which form such working chambers because they may be adequately geared together by way of shafts and some external gears. This possibility suggests that ROPIMA rotors may — up to a point — run at inverse ratios. For example, the outer rotor of an internal axis machine may be made to run faster than the smaller inner rotor and the ring-gear may, for this purpose, have one tooth or lobe less than the inner gear. The term 'tooth' or 'lobe' is rather broadly used in this sense and may signify corners, projections, scallops, involutes and other gear tooth shapes.
The resulting type of engagement is called slip-engagement and is denoted by $\overline{\text{(S)}}$.
Examples of this possibility are indicated in columns III and IV of table 2 but care must be taken in cases where the shafts are connected by gears of equal diameter and have the same number of teeth, because this may indicate that the rotational speeds of the outer and inner members have been inverted.

* Putting the abbreviations between brackets and drawing a bar on top is meant to emphasise that it denotes an engagement method and thereby avoid any possible confusion with other abbreviations.

Textbooks on the theory of machines refer to all sorts of tooth flanks and meshing flanks by the term 'cam engagement' without differentiating between 'cam' and 'slip-engagement' as explained in the preceding paragraphs. Furthermore, in engineering, cam engagements predominate in all power transmitting devices. Slip-engagement on the other hand, which denotes a different relationship between the effective diameters, speed ratios and numbers of teeth is admirably suited to form variable volume working chambers but can hardly, or only with difficulty, be applied to the mechanical transmission of power. These facts seem to justify the distinction drawn between 'cam' and 'slip' engagement.
When a different principle of motion determines the movement of the variable chamber forming components, the arctuate engagement $\overline{(A)}$, the respective engaging parts are guided along circular parallel paths at a speed ratio of 1 : 1.
Arctuate-engagement, at the ratio of 1 : 1, of internal axis machines replaces cam or slip engagements, which cannot be applied to this type of machine. Indeed, in these configurations it is not only the relative speeds of the rotors but their direction of rotation which may no longer be similar in sense and magnitude to those of a pair of meshing gears. For instance, two rotors of an external axis machine, designed to form a variable volume working chamber, may be interconnected by three external tooth gear wheels, hence the rotors will move in opposite directions at their point(s) of contact. This type of engagement is denoted by $\overline{(Co)}$ which indicates that the rotors turn, in fact, in the **same direction** rather than in opposite directions as a pair of meshing spur gears would rotate.
Yet another type of engagement of rotary piston machines is the familiar reciprocating engagement $\overline{(R)}$. It can only be incorporated in planetary-rotation machines which cannot be converted into single-rotation machines:

Table 1 indicates the possible types of engagement besides defining the terms and expressions used, or making them more comprehensible, with respect to tables 2–6, which illustrate the various principles of engagement.
Table 2: internal axis single-rotation machines,
Table 3: external axis single-rotation machines,
Table 4: internal axis planetary-rotation machines with internal rotor,
Table 5: internal axis planetary-rotation machine with external rotor,
Table 6: external axis planetary-rotation machine.

These tables illustrate one version of each configuration, that is diagrammatic sketches showing the respective gearing arrangements, with arrows indicating the direction of rotation.
Engagement occurs when the centres of two parts, of which at least one must move, do not continuously coincide. Envelopment occurs when the centres of the respective parts coincide continuously.
(With regard to these illustrations, it should perhaps be pointed out that sections through the cranks and meshing components may lie in different planes according to the individual design.)
In the case of internal-axis machines any misunderstanding is avoided if it is

emphasised the engagement point is always at the place where the two respective components are closest to one another, that is, where the engagement is deepest and where the enclosed working chamber is smallest. However, in keeping with the principles of this classification, the engaging point does not occur on the opposite side of the two components, where the chamber volume is largest, despite the fact that these components may be sufficiently close to each other to ensure an effective sealing off of the contained chamber.

5.3 Types and models

The overall classification of rotary machines according to the characteristic behaviour of their centres of gravity, the arrangement of the axes of rotation and the methods or principles of engagement (meshing), as explained in preceding paragraphs, was finally condensed to four charts.

Chart 7: internal and external axis single rotation machines (SIM)
Chart 8: internal and external axis planetary rotation machines (PLM)
Chart 9: internal, external and central axis rotating piston machines similar to single-rotating piston machines (SROM)
Chart 10: internal and external axis rotating piston machines similar to planetary-rotation machines (PROM).

Every machine shown on these classification charts represents, of course, only one possible version as indicated by the position it occupies on the chart. Other versions may exist or be devised.

Consequently the system provides for supplementary model sheets for every chart position – see tables 11–26; unfortunately it has been possible to compile only a few of the most important model sheets. Every single design shown on these model sheets could, therefore, replace the model indicated in the appropriate place on the classification charts. It is anticipated that most blank spaces will be filled in as new basic configurations are discovered. If, however, a whole column or line remains blank it may become advisable to investigate the reasons for this and find out whether these models are capable of realisation. In this connection it was, for instance, discovered that it is impossible to convert planetary-rotation machines, relying upon the reciprocating type of engagement, into single-rotation machines. Consequently the lines of chart 7 headed 'reciprocating engagement' have been cancelled. Similarly it has been found impossible to devise external-axis single-rotation machines with arctuate engagement; here too, the corresponding line on the classification sheet was cancelled.

The classification also revealed that every rotary machine – incorporating any fixed ratio of rotation – may be executed in one of two basic inter-related configurations within the limits of their SIM – PLM – SROM or PROM groups – see charts 7–10. Moreover, in the case of internal-axis single-rotation machines no fewer than four such variants are possible. They may be distinguished by the shape and arrangement of their power component (piston or rotor) – see charts 8 and 10.

Penetrating * inner power transmitting component
Penetrating outer power transmitting component
Embracing inner power transmitting component
Embracing outer power transmitting component.

The differences may be clarified with reference to the planetary-rotation machine classified in chart 8 line I columns 1, 2, 3, and 4, which rely upon the reciprocating engagement principle and incorporate therefore the usual piston and cylinder shapes despite the fact that they are in effect true planetary-rotation machines.
The machine in line I column 1 (henceforth denoted by I/1, I/2, etc.) represents, in simplified form — single cylinder instead of four cylinder — an invention originally made by Parsons. However, it must not be confused with the 'Gnôme le Rhône' rotating-piston radial engine which was a PROM type of rotating-piston machine functioning similarly to a planetary-rotation machine. (It appears in the classification on chart 10 I/1.) The machine indicated in I/1 of chart 8 has a penetrating inner power component (piston); the machine in I/4 a penetrating outer power component, while the machine in I/3 has an embracing inner power component and that of I/2 an embracing outer power component.
These four variations may also be obtained for machines with arctuate-engagement as shown in the same chart.
The machines of II/7 and II/6 have penetrating outer and inner power components respectively while the machines II/5 and II/8 have embracing inner and outer power components. It is not quite so easy to distinguish the four variations in the case of other planetary-rotation machines. Nevertheless, all four variations are obtainable for the machines III/5—8 and IV/5—8 or III/13—16. Apparently the four variations of the power component for planetary-rotation machines, indicated on classification chart 8 (PLM), are obtainable, if the working chamber is formed by two moving components only. However if it is formed by three moving parts only two variations seem possible.

5.4 Position of the curve generating points and the sealing elements

The basic configuration of every type of rotary piston machine expounded in part 5.3 above is related to the relative disposition of the curve generating points and the positions of the sealing elements. It is, therefore, essential to distinguish between machines on which the curve generating points and the corresponding sealing elements are part of the inner rotor or member, they are denoted by a suffix 'i', and when they are attached to the outer member, by a suffix 'a'; the respective suffix is always used after the letter which indicates the type of engagement (meshing) applicable to the particular machine.
For instance, III/1 of chart 7 denotes a single rotation machine with cam type engagement and sealing elements housed in the outer member, hence the abbreviated notation would read SIM $\overline{\text{(Ce)}}$; the single rotation machine of III/2 with

* Penetrating is the act of engagement or meshing.

cam type engagement and the sealing elements in the inner member is denoted by SIM $\overline{(Ci)}$. The planetary-rotation machines III/5 and 6 of chart 8 also rely upon cam type engagement and their sealing elements are housed in the inner rotors, their abbreviated notation would therefore read PLM $\overline{(Ci)}$ while the planetary-rotation machines according to III/7 and 8 still rely upon cam engagement and their sealing elements are housed in the outer member, hence their notation would read PLM $\overline{(Ce)}$.

5.5 Notation of relative speeds of rotation (ratios)

In the case of internal-axis single-rotation machines, the rotational speed of the inner smaller rotor is quoted first and then the speed of the outer and larger meshing rotors. Hence, for internal-axis cam-engagement machines $\overline{(C)}$ the first figure is always the larger. For example, 2:1, 3:2 etc. while for internal-axis slip-engagement machines $\overline{(S)}$ the first number is invariably the smaller, that is, 1:2, 2:3, etc.

Similar reasoning is applied to planetary-rotation machines and the same notation applies even when one of the engaging rotors is stationary, that is when its rotational speed has been transferred to the crankshaft.

The same principle is also applied to external-axis single and planetary-rotation machines; it is the speed of the smaller rotor which is quoted first, even if one of the engaging components is stationary.

5.6 Arrangement of the parts which form the working chamber

Apart from the movement of the respective centre of gravity, the method of engagement, positions of the axes of rotation and the locations of the curve generating points, it is necessary to consider the action of the parts which form the working chamber. Four basic possibilities need to be considered. The variable volume chambers may be formed by:

1) The engaging (moving) parts alone.
2) At least one engaging (moving) and one stationary part forming the external working chamber wall.
3) At least one engaging and one stationary part forming the internal working chamber wall.
4) At least one engaging and one stationary part of both the external and internal chamber forming parts.

It becomes apparent in studying the classification that it is expedient to combine methods 2 and 3 as a single possibility, thus obtaining three alternative ways of forming the working chambers of rotary piston machines.

6. Remarks about individual models

Various rotary piston machines are thoroughly examined in this section. They are elaborated with reference to specific inventions which have already become known and the use of the relevant charts is illustrated.

6.1 Reciprocating engagement

Internal axis planetary-rotation machines with reciprocating engagement $\overline{(R)}$ have been shown on chart 8 line I columns 1 to 4 (I/1–4). In each of the machines depicted by I/1 the centre of gravity travels in a circular path at constant angular velocity and the piston rotates about its own centre of gravity, while the cylinder also rotates uniformly about its own stationary centre of gravity. There is only a single piston in this machine suitably extended to incorporate a balance weight which ensures that its c. g. coincides with the centre of the crank-pin. It is, of course, far more advantageous when a pair of pistons is arranged one at either end – as illustrated in several configurations on model sheet PLM I (table 11). A particular model – a steam engine – incorporating two such pistons was, in fact, conceived by Parsons, who is perhaps better known for his work on turbines. Indeed, several of these Parsons engines were installed in ships to drive generators and reports stressed their vibration-free performance. The most notable disadvantage is their large overall size relative to the working chamber volume. Steam inlet and outlet are controlled by a single stationary valve disc, the respective ports being opened and closed as the cylinders revolve and sweep past the openings in the disc. This arrangement probably suffered from considerable steam leakage or friction losses in view of the scant knowledge of sealing rotary disc valves available at that time.
Parsons' machine was preceded by Witty's (1811), whose design is shown in the third line of table 11. A trunnion or block and stationary pin (or, as it is sometimes called Scotch yoke) was used in place of a crank. Andrew's steam-rowing machine (1858) table 11 II/3 also belongs to this category. There is no crank in this design, the correct piston movement being ensured by a trochoidal cam plate which moved at a ratio of 1 : 2. An internal combustion engine according to this principle is, for example, the Bucherer engine.
An external-axis reciprocating piston machine, designed by the author in 1929, is shown at I/11 of chart 8. In this, both the piston and the cylinder were given a parallel circular motion. The size of this type of machine relative to its stroke volume is more advantageous than for internal-axis machines with reciprocating engagement. However, the continuously shifting radial strain is less desirable than the centrifugal strain in the revolving cylinders of internal-axis machines.
In the patent specification there was a reference to the possible use of this type of fully balanced mechanism for machine tools. Since 1950 it has become known that the high-speed blanking press produced by 'Lempco Products' incorporates a device of this kind.

6.2 Arctuate engagement $\overline{(A)}$

Single- and planetary-rotation machines with arctuate engagement $\overline{(A)}$ are shown in chart 7 II/1–4, 6, 8 and chart 8 II/5–8, 11. Galloway probably invented the first internal-axis planetary-rotation machine in 1846, see model sheet (chart 1) SIM II 2 (table 12), line 3 No. 2. He used it as a marine steam engine but in the absence of sealing elements its performance was unsatisfactory.

A. Lind suggested in 1914 an internal-axis single-rotation four stroke engine with arctuate engagement, see table 12 II SIM 2, line 1.

Machines with constantly shifting contact points between the engaging components may only be sealed by a special grid arrangement in which the sealing elements contact each other, thereby blocking practically every possible leakage path. Machines with arctuate engagement also feature continuously shifting contact points but it is a peculiarity of the arctuate engagement that every point of the engaging parts circles in a parallel path to all other points; thus sealing may be effected by means of relatively few sealing elements. The sealing elements must protrude slightly out of their grooves in order to seal effectively. These elements subdivide the large curved segments of the meshing component into a number of smaller circular segments but the sealing contact shifts from side to side in sequence.

C. H. Varley invented the paracyclic single-rotation pump in 1919 and fitted a sealing system, as described above, during the development stage. However, the author was obliged to rediscover this type of sealing arrangement in 1947 during his work on single-rotation engines with arctuate-engagement features. This exertion was necessitated by the absence of a comprehensive reference and classification system for rotary piston machines, and single-rotation machines in particular.

In position II/11 of chart 8 is shown, as an example, the planetary-rotation external-axis machine invented by Köpke in 1942.

6.3 Cam engagement $\overline{(C)}$

Internal-axis single- and planetary-rotation machines featuring cam engagement $\overline{(C)}$ and incorporating trochoidal curves are shown in position III/1 and 2 of chart 7 and in positions III/5–8 of chart 8. Single-rotation machines with significant trochoidal curves may be realised in two versions, namely as internal- or external-rotor machines in which the curve generating points and sealing elements are part of the respective inner or outer rotor.

In the case of planetary-rotation machines with trochoidal curves, four variants are possible; two with internal- and two with external-rotors. The curve generating points and sealing elements are part of the inner-rotor in one case and in the other they are part of the outer rotor; in the 3rd and 4th cases they are part of the stationary inner- or outer chamber wall respectively.

Single-rotation machines SIM III/1 (chart 7) were invented by Cooley in 1901 in the form of steam engines. Various attempts have been made since to apply this basic principle to planetary-rotation internal combustion engines, for example, by

Umpleby in 1908 and later by the Renault Company. The attraction of this configuration is undoubtedly the way in which the working chambers are formed almost without parasitic displacement. The Japanese ISUZU company produced in 1963 a SIM type four cycle engine with a relative speed ratio of 3:2. This engine featured simple inlet and exhaust ports which were accommodated in the inner rotor. E. Höpner who examined such a configuration in 1954 decided not to pursue this design when he found that the inlet and exhaust gases necessarily pass through the shaft. The ISUZU design resembles, to some extent, known $\overline{\text{(SIi)}}$ engine configurations which have a 2:3 speed ratio, its inner rotor possesses the characteristic figure eight trochoidal shape. The outer rotor envelopes the inner rotor as well as accommodating the sealing elements, hence there is an unfavourable relationship between engine bulk and the displacement volume. However if the engine is built as a planetary rotation unit (PLM) part of the power must be transmitted by gearing which is not considered an advantageous expedient. Furthermore, the requirements of adequate port sizes and opening periods of PLM engines cannot be easily satisfied by the configuration. For example, it is possible to accommodate the unavoidable ports – as on two-stroke engines – in the end-covers. Unfortunately, it is impossible to dispense with a precompression phase for much the same reasons as in ordinary reciprocating-piston two-stroke engines – that crankcase compression is utilised to ensure efficient exhaust scavenging and charging of the engine. Provision of adequate port areas leaves only relatively short phases available for the compression and expansion of the gases. According to a study pursued by Ernst Höpner in 1957 rotating disc-valves – one on either side – are essential if the four-stroke cycle is to be accommodated. Engine weight is thereby increased and if the planetary-rotation principle is applied considerably higher bearing loads are obtained due to centrifugal forces. The increase in engine bulk is, of course, also undesirable.

Leaving aside poppet valves, the only other possible timing of port opening is by way of rotary valves driven at an appropriate speed. Earlier internal combustion engines of this type failed partly because of these problems, but in particular because of sealing difficulties.

Since parameters of the NSU-Wankel engine and its sealing system have become known, Renault and others have decided to continue development work on Cooley type planetary-rotation internal combustion engines.

Chart 8 – PLM III/7 and sheet 13 of the classification shows that machines based on the same principles and incorporating identical speed ratios may look very different from each other. If in a machine with a speed ratio of 2:1 the rotor is of circular section or if the rotor flanks are made of circular arcs, the rotor may move between the parallel walls of a cylindrical tooth gap. This phenomenon is the same as the locus of a point on the pitch circle of a planet pinion which rolls inside a base circle of twice the diameter of the rolling planet, being a straight line. A diagrammatic sketch of this type of machine is shown in line 2, column 1 of table 13. This machine with its circular rotor and arena shaped bore has a resemblence to the configuration shown in the line above it in the table, except that the latter combines a circular rotor with a trochoidal bore. The difference between the two designs is

that whereas there are only two curve generating (contact) points in the design with the trochoidal bore, a multiplicity of contacts, on both sides of the bore, occurs in the design incorporating the straight sided arena shaped bore.
A section through the planetary-rotation pump invented by Moineau (French patent No. 400,508), with screw-type engagement, is similar to the machine illustrated in table 13, second line, first column. However, Ludwig Taverdon of Paris obtained a patent for this type of configuration as long ago as 1878.
Retaining the 2:1 speed ratio but introducing two or more circular rotors produces a design similar to the steam engine design patented in 1901 by Franzen and Fahlbeck.
Witte patented a similar diesel engine configuration in 1949. Even if it is possible to master the sealing problems of machines with spherical or rolling cylindrical pistons parallel to the axis of rotation, the resulting machines of this type will not be very desirable. This applies particularly to multi-rotor designs, as unfavourable relationships exist between the displacement volume and the necessary overall bulk of the machine because twice as many cylinders are required as pistons. Only when one double acting piston – first figure table 13 second line – is used is it possible to obtain a favourable displacement/overall bulk ratio.
If, however, this design is converted to a single-rotation machine, for which purpose its piston-rotor will be mounted eccentrically on its shaft while the housing becomes the revolving sealing component, it is possible to re-convert the SIM machine thus obtained, into an easy-to-seal planetary-rotation machine with reciprocating engagement. Accordingly it proved necessary to convert the rotor of the single-rotation machine into an eccentric by mounting on it a planetary-rotation rotor. The resulting configuration is shown in table 11, line 2, column 1.
(To illuminate a little more the multifarious relationships between rotary piston machines in general, it should perhaps be pointed out that this reciprocating-engagement planetary-rotation machine is closely related to the planetary-rotation machine shown in table 19, line 2 column 1 [by Beale]; the power transmitting component of this machine possesses reciprocating-engagement and simultaneously performs the function of a pair of vanes. These vanes revolve in the stationary trochoidal bore with slip-engagement!)
It is possible to derive from the machine shown in table 13, line 2, column 1 a unit with round piston rotors as shown in lines 2 and 3, column 2, which show the rotor in multiple piston form. In addition, it was possible to double the number of generating points and sealing elements, for machines with a speed ratio of 4:3 as shown in table 13 and obtain piston rotors of quite different shapes. For the chosen example it was possible to retain the number of teeth and gaps. It is, however, equally possible to reduce the number of teeth and gaps respectively to six each without having to alter the position of the eight sealing elements.
Wallinder and Skoog proposed a planetary-rotation four-stroke cycle engine with a speed ratio of 6:5, as shown in table 14, in 1923. Sensaud de Lavaud on the other hand experimented in 1938 with a single-rotation engine, see chart 7 (SIM) III/2, table 15. In its basic form there are only small parasitic cylinder volumes (maximum

cylinder volume minus stroke volume) in this design and the ports may be opened and closed by rotor movement. Unfortunately, gas flow requirement demand that parts of the inner rotor are scooped out in order to provide adequate port opening areas and periods, which increase the parasitic volume in each cylinder and, in turn, make it practically impossible to realise present day compression ratios.
It is by no means easy to recognise in every instance whether a particular rotary-piston engine proposal is capable in its simplest form of accomodating the four-stroke cycle. Of the $\overline{\text{(Ci)}}$ machines just examined only those with speed ratios of 4:3 and 6:5 etc. may be designed in a form suitable for four-stroke operation. Of the $\overline{\text{(Sli)}}$ machines discussed in section 6 and 4 above only those with speed ratios of 2:3 and 4:5 etc. are capable of accommodating the Otto-cycle. Of all other trochoidal configurations, including $\overline{\text{(Ce)}}$ and $\overline{\text{(Sle)}}$ types, some are quite unsuitable for the application of the four-stroke cycle while others provide additional phases, such as secondary expansion, scavenging or even a supercharging phase, and the engines become special-cycle engines. Only by way of rather complex mechanisms and additional timing devices can these configurations be adapted to the four-stroke cycle.
Various derivations of trochoidal machines are shown on chart 8 (PLM) III/5 (table 14). For example, a trochoidal machine having a 2:1 speed ratio was changed into a single-rotation machine with a piston rolling round the bore. Reference should perhaps be made, in this connection, to the straight line locus traced by a point on the periphery of a rolling circle while rolling inside another circle of twice its diameter. The flanks of the housing 'teeth' are, therefore, straight sided. Beneath the trochoidal machine, with a speed ratio 3:2, is a flat vane rotary piston machine as proposed in the early forties by di Blasi for aircraft superchargers. Machines of an entirely different shape were obtained with speed ratios of 4:3 and 5:4 by altering their eccentricity, that is their crank throws.
The bottom line of the diagrammatic sketches shows machines having speed ratios of 2:1, 3:2 and 5:4, their greatly varying chamber shapes being due to doubling the number of generating points and sealing elements (of the models shown above). It will be noted that on machines with speed ratios of 3:2 and 5:4 the inner rotors penetrate their engaging members almost in the fashion of reciprocating motion between practically parallel flanks, which look like cylinders in the sectional sketches.
In 1950 the author made a design study of a 5:4 speed ratio machine using twice the number of curve generating points and tip-seals. In fact it was the development of these radial tip-seals in conjunction with the interlocking axial sealing plates which formed the last but one step towards the development of the sealing system for the first $\overline{\text{(Sli)}}$ four-stroke engine with a 2:3 speed ratio.
Internal-axis machines, resembling gear type pumps, as used for heavy oil and other fluids, are shown on the model sheet of single-rotation machines, that is in chart 7 in positions III/3, 4 and 8. This arrangement was also intended to perform as an internal combustion engine. Indeed, it has even been patented for this purpose as exemplified by the two-stroke engine evolved by Brown and Bovery in 1924.

It is possible to devise machines in which a secondary crank rotates about a primary crank (or eccentric); the rotor itself being mounted on the secondary crank. This type of crank upon crank arrangement is prominent on the Doyer or Ruf engines, their rotors revolve at a constant speed which is ensured by suitable gearing. The triangular locii of the respective rotor corners resemble somewhat pointed hypotrochoids due to this double crank arrangement; moreover, the mechanism is fully balanced but the second crank pin is expected to cope with greatly fluctuating centrifugal loads.

The following basic principles apply to machines which feature this crank upon crank (double crank) arrangement.

The respective machine may be either a PLM or PROM machine. If the phasing depends exclusively upon rotor or crank motion, which is controlled by centrally mounted gearing, the respective machine may be either an REM (reciprocating) or PLM (planetary-rotation) machine. Both these machines can be completely balanced.

This double or even treble crank arrangement (crank rotating about a crank pin which is itself revolving about a pin — which also rotates about yet another crank pin) may be applied to rotary or reciprocating-piston machines because the locus of their respective power transmitting rotor (piston) may be practically a circle, a pointed or even looping trochoid or a straight line. Examples of the last mentioned configuration are the machines developed by Pickert or Jones in which the revolving connecting rod, formed by gears, constitute a second crank.

On the same sheet in positions III/9 and 10 are shown internal-axis machines which incorporate short trochoidal curves but no stationary chamber walls because these are formed between the meshing members themselves, in fact between the tooth in one member and the corresponding gap in the other. The actual displacement volume is relatively small and depends upon the tooth profile and proportions. A steam engine design according to this principle was patented in 1903 and 1904 by Jacquet of Strassburg-Königshofen.

Internal-axis internal combustion engines with one power transmitting and one sealing rotor which are enveloped by a common housing, as shown in chart 7 (SIM) III/11, seem to attract the attention of many inventors. It would be equally correct to show one of the widely used external axis gear pumps accommodated in a housing with a similar figure eight bore in place of the example. In this type of single-rotation machine there are no parts which move at variable speed; it was invented in 1636 and is known as the Pappenheim pump. It is interesting that in 1799 Murdock, the congenial collaborator of James Watt, fitted wooden sealing strips in the tip of every tooth and built several of these units as steam engines. Considerable leakages were experienced due to the absence of end-seals and to the inherent inaccuracies of manufacturing methods of the period.

An invention made in England by Jones in 1848, which since 1866 has become known in America as the Roots blower, does not really lend itself to conversion into an engine although it was patented in its oldest form by Holt and Jackson in 1841 as a steam engine. Configurations with inner stationary chamber walls are shown in chart 7 (SIM) III/12 and 14 while chart 7 (SIM) III/15 and 16 show external-axis machines with both internal and external working chamber walls. The design according to chart 7 (SIM) III/16 was invented by Behrens in 1867 and it was executed in the form of pumps and steam engines; in view of the prevailing low pressures it was unnecessary to incorporate any sealing elements: the large areas and close running clearances imposed adequate restrictions.

On the classification sheet for planetary-rotation machines there is a design in position III/11 (chart 8) which incorporates a turning rotor with spherical type pistons — teeth — orbiting in a circular path which engage in similarly circulating bucket type cylinders pivot mounted on a rotating base.

Four external-axis planetary-rotation machines with non-rotating outer chamber walls are shown in chart 8 (SIM) positions III/13 to 16. Not unnaturally the figure eight type bore, so prominent in external-axis single-rotation machines is not required; one of the engaging components assumes the functions of a non-rotating housing which, depending upon the particular design configuration, may — in either an enveloping or penetrating form — become the outer or inner working chamber wall.

When a planetary-rotation machine possesses the figure eight type bore, the bore assumes the functions of a sealing component (containing the working medium) which revolves in unison with the engaging component about the stationary member of the arrangement.

6.4 Slip engagement

Single-rotation configurations of internal-axis slip-engagement machines with trochoidal bore or rotor contours are shown in positions IV/1 and 2 (chart 7) and single rotation versions in positions IV/5—8 (chart 8). In 1935 Fixen described slip-engagement machines with outer curve generating points in his patent specifications. His planetary-rotation $\overline{\text{(Sle)}}$ machines with speed ratios of 3:4 and 4:5 are to be found in chart 8 PLM positions IV/7 (table 16). Fixen designed his machines to have helical slip-engagement.

Single-rotation machines as shown in group SIM position IV/1 (table 7) and a planetary-rotation version with 2:3 speed ratio shown in chart 8 PLM position IV/7 (table 16) were patented by Maillard in 1943 and, indeed, several experimental aero-engine compressors were made according to these principles. This type of configuration is unsuited to the four-stroke cycle because the locations of curve generating points, that is of the sealing elements, do not divide the chambers of any $\overline{\text{(Sle)}}$ designs in the requisite manner.

Slip-engagement machines with inner sealing elements $\overline{\text{(Sli)}}$, as shown in position IV/2 (chart 7) and chart 8 (PLM) IV/5 (table 18), and with speed ratios 1:2 which have been known since 1834 as steam engines were designed by E. Galloway. However, they were mostly manufactured in the form of blowers and compressors. Indeed, Planche (France) is still producing planetary-rotation compressors of this type, albeit with flat spring steel type valves. To convert this type of machine into an internal combustion engine it is, however, necessary to incorporate a rotary valve. Alternatively, it could be made into an engine by providing two units in parallel, one to function as a compressor and the other as the expansion or output device.

Although slip-engagement machines with speed ratios of 1:2 and inner sealing elements (Sli) as well as the above mentioned – though not generally known – slip-engagement machines with outer seals (Sle) existed, no attempts were made to evolve other (Sli) machines with different speed ratios. This may be due to the absence of groupings or classifications of rotating piston machines relative to their methods of engagement, and which took into account the location of the curve generating points. It is, however, possible that it was thought that chamber forming (Sli) machines with a speed ratio of 1:2 were simply a special epicyclic gearing arrangement offering a particular speed ratio, that is if any thought at all was devoted to the problem.

Reference has already been made in section 6.6, dealing with reciprocating and slip-engagement machines, as to how (Sli) machines with ratios of 2:3, 3:4 etc. were in fact discovered. The (Sle) type of machine can function as a four-stroke cycle engine; indeed it was the invention of this type of machine which precipitated the sudden and intensive interest of the motor industry in rotary piston internal combustion engines.

Inlet and exhaust ports of (Sli) type four-cycle engines are automatically timed by the movement of the inner rotor. Ports and opening periods may be considerable without having to cut away parts of the rotor. The minimum volume contained in the chamber is small enough to make possible the achievement of any compression ratio as required for modern Otto-cycle engines but the much higher compression ratios demanded by the diesel-cycle necessitate a reduction of the distance between the centres of rotation or the incorporation of a compressor. Unfortunately, a reduction in eccentricity automatically reduces the displacement volume, consequently the overall proportions of diesel engines are necessarily greater than those of equal displacement Otto-cycle engines. The (Sli) type machines with a speed ratio of 3:4 shown in table 7 (SIM) IV/2 (table 17) or table 8 (PLM) IV/5 (table 18) represent single- and planetary-rotation engines with additional expansion or charging chambers while machines with 4:5 speed ratios may have two inlet and outlet phases or, alternatively, incorporate a charging and a secondary expansion phase. Attention should be drawn to the fact that in (Sli) machines the minimum volume of each chamber increases as the speed ratios go up so that adequate compression ratios can only be achieved by reducing the distance between the centres of rotation – the eccentricity.

6.5 Counter engagement (Co)

Counter engagement single-rotation machines are shown in line V of chart 7 and planetary-rotation machines in chart 8. Scheffel (Germany) was granted a patent for the single-rotation machine of chart 7 (SIM) V/10, which incorporates no circumferential chamber walls, while an American patent was granted to H. Walter in 1957 for the gas generator of chart 7 (SIM) V/13. However, it is significant that counter-

engagement machines of both arrangements were, in fact, invented a long time before the two examples quoted above.
Machines incorporating the counter-engagement principle show even more clearly than those relying upon the slip-engagement principle that engaging components, which cannot transmit power, may form variable volume working chambers.

6.6 Reciprocating and slip engagement

No rotary piston machine which incorporates reciprocating engagement or possesses reciprocating motion may be transformed from a planetary- into a single-rotation unit. This fact has probably been noted before and may be the reason why planetary-rotation machines which can be converted have, in fact, remained untouched for a very long time. The internal-axis planetary-rotation machines shown on chart 8 in positions VI/5 and 8, which may rely upon reciprocating as well as slip engagement, tend to strengthen this belief because they rely upon the reciprocating engagement principle and cannot, therefore, be converted into single-rotation machines. The units of chart 7 SIM VI/5 and SIM VI/8 have trochoidal rather than circular bore shapes and the housing containing the bore are stationary.
The machine according to SIM VI/5 (see table 19) was invented by Franchot in 1861, furthermore it is often associated with the name of Oldham who patented a paddle wheel in 1826 based upon the same kinematic conception. But, contrary to multi-vane rotating-piston machines, whose power transmitting component – that is the centres of gravity of the vanes – pursue a near circular path at variable velocity, these planetary-rotation machines incorporate straight through vanes whose c.g. move in a circle at twice their actual rotational speed. Woodcock incorporated a pair of straight through vanes, as did Zoller in our time, thereby forming four sickle shaped variable volume chambers. This configuration has been used to a certain extent in the form of superchargers for internal combustion engines and in the form of compressors.
The vanes of older versions of this type of machine were guided by the trochoidal bore. A later design incorporated a sliding block arrangement, also known as 'Scotch Yoke', which was followed by the Zoller principle in which each straight through vane is guided by an inner stationary ring. For this purpose the vanes are suitable shaped – see table 19 line 2. The author preferred at first to link the vane to the crank and later he shaped the vane centre to perform a rolling motion round a stationary pin, an arrangement better suited to deal with the centrifugal forces than the indirect method of allowing the centrifugal forces to increase the main bearing loads – see table 19, line 4.
A comparison may prove instructive. Place next to each other the following illustrations: the slip-engagement $\overline{\text{(Sli)}}$ machine of chart 8 (PLM) IV/5 (table 18), the reciprocating-engagement machines of chart 8 PLM I/1, 2nd place, 1st line (table 11) and the combined slip- and reciprocating-engagement machine of chart 8 PLM VI/5, 3rd line No. 1 (table 19). The relationship of these three machines becomes apparent at once, although only the first of these may also be found on chart 7 SIM IV/2 of

the single-rotation design (table 17); the inner rotor of this configuration functions as a sealing component. The second machine cannot be made into a SIM unit on account of the reciprocating motion within the working chamber, neither can the third machine because of the reciprocating motion of the sealing component.
It is perhaps pertinent in this connection to show by way of example how the development of rotary piston machines was hampered by the absence of a sensible classification system capable of providing a comprehensive picture, and of indicating the relationships between different design configurations and of showing up basic principles of design. When the author was working on this comparison he was unaware of the above mentioned $\overline{\text{(Sli)}}$ machines which have 1:2 speed ratios and a pair of vanes each as they were not included in Reuleaux's 'Theoretical Kinematics' dated 1876 or in the 'History of Rotary Engines and Pumps' – The Engineer 1939 – or in Tänzler's work of 1949 on 'Rotary Piston Pumps and Engines' VDI proceedings volume 91 No. 10. While preparing drawings of various bearing arrangements of straight through vane type power transmitting components, as shown, for example, in the first volume of chart 8 (PLM) VI/5 (table 19), it occurred to him to replace the drum-like inner sealing component by a lens-shaped vane. In this way he reinvented the $\overline{\text{(Sli)}}$ type planetary-rotation machine with a speed ratio of 1:2 and only one moving part – see chart 8 (PLM) IV/5 (table 18). Because he was unaware at the time of the basic principles of the inconvertibility of planetary-rotation machines with reciprocating-engagement, and of external-axis planetary-rotation machines with arctuate-engagement into single rotation machines, despite the abandoned drum-like sealing component, it was not until 1953 that the thought struck him of letting the outer member rotate. Thus, the inner rotor could revolve round a fixed centre to form a single-rotation machine – see chart 7 (SIM) IV/2 (table 17). It was observed that in this type of single-rotation machine the relationships between the speed of rotation and the number of teeth compared with the meshing action of an annulus gear and an external tooth pinion. A design investigation was therefore commenced in 1954 with a view to evolving machines with other inverse speed ratios, such as 2:3, 3:4 etc. The $\overline{\text{(Sli)}}$ machine, found in this way, with a 2:3 speed ratio became the first really practicable rotary-internal combustion engine.

6.7 Slip and counter engagement

Planetary-rotation machines with reciprocating and slip-engagement have been elaborated in part **6.6.** of this book and shown in line VI (chart 8). These machines have, at one and the same time, two different modes of engagement. In addition to the single and planetary rotation machines shown in charts 7 and **8**, slip and counter engagement machines appear in line XII.
The single-rotation machines of XII/1 and 4 (chart 7) are attributable to BICERA (British Internal Combustion Engine Research Association), a British research institute supported partly by the state and partly by industry. The design represents experimental engine superchargers of which the sealing components – inner

rotors – are in slip engagement with the outer wall of the rotor and in counter engagement with its inner wall. These machines are shown as a planetary-rotation type in chart 8 at XII/9.

An earlier pump developed by Ritz and Schweitzer is shown in XII/8 (chart 7). It may be noted that while the vanes of the BICERA blower are simultaneously in slip and counter engagement, those of the Ritz and Schweitzer pump are either in slip engagement with the inner rotor wall or in counter engagement with the outer rotor wall.

The same mechanism is shown in the form of a single-rotation machine in line XII/6 (chart 8).

6.8 Additional rotation and circular motion

It is possible to create mixed models by giving certain moving components additional rotation or circular motion. It is, for example, possible to give additional rotation to the rotor of the planetary-rotation machine shown in columns 5–8 of chart 8, line II, III or IV, which consists of a rotor which is mounted on a crank pin and a stationary inner or outer chamber wall. Chart 20 indicates diagrammatically the rotor of such a machine in different angular positions and table 21 depicts several machines, one part or the other having been given additional motion.

In general, rotating piston machines should be designed without additional motion unless this movement is essential for the formation of the variable volume working chambers. In special cases it may be expedient to let otherwise stationary components move in order to effect timing of port opening periods or to enable a component to transmit power.

Occasionally inventors have incorporated superimposed movements in their designs without any obvious reason, a trend which seems especially prominent in single and planetary-rotation designs.

When one or more unnecessary additional motion has been superimposed on essential movements, it becomes most difficult to decide the type of basic configuration under examination. The machine in table 20, quoted above, is difficult to analyse although it incorporates only two rotors. Analysis becomes even more difficult if the particular machine has a plurality of moving parts.

It is sometimes essential to recognise superimposed movements because any additional motion given to the c.g. of a component, which has up till then moved at variable velocity, may conceivably give this component uniform velocity. If this has, in fact, been achieved the assumed superimposed motion must be evaluated as a specific movement of the particular design.

7. Remarks about rotating piston machines

It does not follow that every moving part of single or planetary-rotation machines has inherently uniform rotary or circular motion. Consequently, the number of possible configurations is virtually unlimited. Moreover, any single and planetary-rotation unit may be converted into a rotating piston machine by relying upon eccentrically mounted or out-of-round gears which are attached to the shafts of power transmitting and sealing components which mesh with suitably shaped parts. Single and planetary-rotation machines which are thus made less tenable than might otherwise by the case are not, of course, included in this classification. Only those configurations have been added whose functional characteristics are due to variable rotary or circular motion.

Naturally, it is possible to distort any single or planetary-rotation machine by incorporating parts which have variable speed, thereby obtaining further types of rotating piston machines. But they are of no practical significance as far as this analysis is concerned.

While for pure-engagement methods by far the greatest number of different single and planetary-rotation machines are to be found in lines I to V, in the case of rotating piston machines the greater number of variants seem to be found in the lines reserved for mixed-engagement principles.

It may safely be assumed that most inventors of single and planetary-rotation machines have a justifiable aversion to the rather complex mixed-engagement methods. These inventors have probably eschewed components moving at variable velocity and they may, in some cases, have been unaware of the many possible alternative configurations with uniform velocity. Perhaps there are other underlying causes. Whatever, the reasons, they seem to have induced the successors of Ramelli (1588) to devote their inventive talents to single or planetary-rotation machines which relied neither upon the derivations of pure methods of engagement nor upon mixed-engagement principles.

Some inventors seem to be undisturbed by the fact that the uniform motion of the main components of their inventions depend upon the variable velocities of supplementary parts. Others have avoided supplementary parts by giving variable rotation or circulating velocity to the main moving components themselves. Consequently very few rotating-piston machines achieved even briefly performances which equalled or surpassed those of reciprocating piston designs. The vast majority proved decidedly inferior. Often the manufacture of these machines proved more difficult than that of comparable reciprocating piston devices. The shapes of individual parts and their guidance or bearing arrangements failed to permit the achievement of the higher rotational speeds, and they posed rather complex sealing problems.

7.1 Circular outer shape

Planetary-rotation type rotating-piston machines are shown in position XI/5 and 13 of chart 10. These merit attention because clearly they may be divided into internal and external-axis machines. However, they were invariably grouped together in previous classifications because of their actually or apparently round outer shape, while external-axis machines, such as gear type pumps or Roots blowers, were placed in different categories on account of their figure eight type bores. Closer examination of the designs, shown in line XI, reveals that the figure eight type bore is in fact present in column 13, though in rather indistinct form. The second axis of rotation is outside the area swept by the moving rotor and the mode of engagement is similar to a pair of meshing spur gears, though not in the same sophisticated form. It seems essential to resist the temptation to classify these outwardly completely round configurations as internal-axis machines. Due to the presence of a second axis of rotation it is therefore possible to differentiate between internal and external-axis planetary-rotation type rotating-piston machines as shown in lines X and VIII. However, this differentiation is somewhat blurred in the case of the machines of line VI and VII as there is no second axis of rotation; these machines can only be identified by referring to the above mentioned versions.

7.2 Reciprocating engagement

In I/1 of chart 10 of the classification sheet of planetarv-rotation Rotating Piston Machines is a unit designed in 1907 by Seguin as a radial aircraft engine which was, among others, manufactured by Gnôme le Rhône. This rotating engine proved to be the first internal combustion engine to get down to a weight of 2.2 lb/B.H.P.; while its revolving radial cylinders were undoubtedly well cooled, the gyroscopic effects of these rather substantial rotating masses influenced aircraft manoeuvrability and excessive amounts of oil tended to find their way into the cylinders. Radial engines with stationary cylinders were, therefore, soon preferred although they suffered from the same inertia effects as the reciprocating piston engine.
It is doubtful whether some machines described as 'Rotating Piston' can justify the denomination. An example is provided by the external axis PROM machines shown in I/11 and 12, where the reciprocating cylinders or piston parts are relatively heavy. However, as in all rotating piston (ROM) type machines, the moving components have variable velocity so their size and weight places them outside this consideration.

7.3 Cam engagement

Machines with spherical or transverse cylindrical teeth which engage in suitable round or parallel wall bores (rectangular section) are shown in positions III/1–4, 9, 11, 12, 15 of chart 9 and in positions III/5–8, 11, 15, 16 of chart 10. Because the components containing the bores somewhat resemble Maltese Crosses they turn or move in a circular orbit at variable velocities. Only two configurations are known which facilitate uniform motion, namely:– the internal axis configuration with a speed ratio of 1:2 if the hypocycloidal principle, for the condition base circle radius R = 2 rolling circle radii, is applicable (see part 6.3 and model Chart 8 (PLM) III/7 (table 13), line 2 No. 1 and line 3 No. 1) or, as in the case of external axis machines, the female parts, i. e. the components containing the bores, rotate parallel to the component with the spherical (or cylindrical) mating parts – see classification chart 8 (PLM) III/11. The oval gear principle, as used for certain counting machine mechanisms (for instance, the petrol gauge manufactured by Bopp & Reuther) is shown in SROM III/13 (chart 9). Its conversion into a planetary rotation device is indicated in PROM III/14 (chart 10).

A machine with a speed ratio of 4:3 is shown in PROM III/1 (chart 10), which may at first be classified as a single-rotation unit with uniform speed. On closer examination it will be found, however, that at least one of the meshing components must possess variable velocity because the profiles are not trochoidal. This variable rotary velocity is obtained either by ensuring that the outer member is given an additional rotation – although the inner (3 tooth pinion) is already free to revolve round the crank pin – or by providing another crank pin which must be free to turn about the centre of the first crank pin. The pinion is, of course, free to revolve round the second crank pin. The last design is, of course, a double crank ROM (rotating-piston) machine.

7.4 Slip engagement

Very few arrangements of planetary-rotation type machines with slip-engagement have become known. Among the rare examples is a British design by Huxley (1865) and the Spanish Patent No. 268,765 granted to Martinez Ortega in 1961 as shown in PROM IV/7 and 8 (chart 10). In Huxley's design the correct piston-rotor movement is due to one crank mounted on and orbiting round another crank pin, while in Ortega's configuration the two or three arc rotor engages with a similarly shaped outer member due to the appropriate action of two meshing gears; thereby the rotor is made to move in or round the other two or three arc component. The locus of the centre of gravity of this rotor is no longer similar to a circle although it is in fact a completely closed path with two apexes. This type of machine contains **no** minimum volume at all but this advantage is nullified by the crank-upon-crank arrangement and the problems arising out of the oddly shaped internal tooth gear and by the greatly fluctuating velocity of the power transmitting component.

As only $\overline{\text{(Sle)}}$ and $\overline{\text{(Ce)}}$ configurations were mentioned in the Ortega patent specification, the related $\overline{\text{(Sli)}}$ machines have been added to columns 5 and 6 of the classification chart.

7.5 Reciprocating engagement and engagements similar to slip engagement

Two of the oldest rotary piston machines are shown in chart 9 at VI/11 and in chart 10 at VI/5; both were described in 1588 by Ramelli. Many different versions of these machines have been built in the intervening years; indeed they have even been reinvented, in particular the design indicated in chart 10 (PROM) VI/5. Ramelli probably built his machines with only one sliding vane and it was not until the beginning of the present century that Wittig evolved the multi-vane version which has become widely known in the form of a compressor or blower. The housings of these blowers were equipped with special bearing surfaces capable of dealing with the centrifugal forces due to the vanes. The relative sliding velocity between the vanes and these bearing surfaces is comparatively low but for the faster moving designs minimum running clearances between the vanes and the housing are relied upon rather than high pressure oil-film sealing. The rotating members revolve at full speed and are expected to seal effectively the leakage paths at the ends and between the slot and the vane. Complex sealing elements were, therefore, incorporated in some designs for this express purpose. Although this kind of vane type compressor has been carefully developed by reputable companies, it is meeting increasing competition from single-rotation and Roots type blowers even in the low and medium pressure field. Indeed, in the aircraft field Roots superchargers had virtually replaced the vane type blower before the beginning of the 'twenties'; a process which was repeated in the automotive field. Meanwhile, yet another single-rotation machine, namely the Lysholm-compressor, has become widely used for stationary compressor applications.

Further single and planetary-rotation machines will undoubtedly be designed although the inertia effects due to the near circular path which the c.g. of each vane pursues at variable velocity impose speed limitations. Care, of course, is taken so that the individual vanes of rotating-piston machines are as thin and light as possible. However, the vanes slide considerable distances out of the central drum besides being exposed to working pressure. They must not, therefore, be so thin as to bend under working conditions and so hamper their free sliding motion.

Chart 10 (PROM) VI/5 (table 22) shows a number of designs based on the original Ramelli idea. All suffer from fundamental, and inevitable, disadvantages. These handicaps have been responsible for the failures of various attempts to convert this type of rotating piston machine into an internal combustion engine. Only transitory successes have become known. The first partially successful example recalls the steam engine designed in 1899 by O. W. Hult in Stockholm and manufactured in Germany by the Kieler Maschinenbau A.G., who produced various sizes of engines which developed 35—113 B.H.P. The aggregate power of the engines built amounted to about 6000 B.H.P.

The other Ramelli machine shown in VI/11 (chart 9), in which a sealing element is moved in and out of its slot by the eccentric or cam shaped rotating piston, has been made frequently in the form of pumps besides having been applied to engines. Yule's steam engine of 1836 provides an example. It incorporated only a single reciprocating and sliding sealing element. Two similar sealing components featured on the steam engines designed by Bährens (Germany) in 1847, D. Napier (England) in 1851 and Bompard (Italy, Piemont) in 1867 are thereby divided by two equal working chambers. It was, of course, unavoidable that as soon as the gas engine was invented attempts would follow to apply Ramelli's configuration to internal combustion engines. I. H. A. M. Brunklaus was one aspirant. Indeed, he is referred to as a pioneer in an historical account of German internal combustion engine development published in 1962. The impression is given by this publication that he was the first to make and run a single-rotation gas engine as outlined in his Dutch patent No. 26,198 dated 1929. It is understandable that no references were made to the speed, power output, endurance and fuel consumption of this engine but it is incomprehensible that historical facts which are, after all, so easily verifiable from patent specifications, books and periodicals, have been distorted in this way. Long before Brunklaus or his engine, which incorporated poppet valves, there were quite a number of equally unsuccessful inventors some of whom tried to convert planetary or single rotation machines into internal combustion engines; Fred Umpleby (England) in 1909 produced just such an engine which now reposes at the Keighley museum in Yorkshire.

7.6 Arctuate type of engagement

Some widely known vane type machines are shown diagrammatically in chart 9 (SROM) IX/1–4, 6 and 7. Although this arrangement permits complete balancing of the vane rotor, either the vane-rotor itself or the sealing component must possess variable velocity in accordance with the particular design configuration; only by providing excessive clearances between the vanes and the circular sealing components is it possible to make the machines of chart 9 (SROM) IX/1–4 into true arctuate-engagement machines of table 7 II/1–4 in which all parts rotate at uniform velocity.

Chart 9 (SROM) IX/3 (table 23) shows a variation of these vane type machines which incorporates pins, cylindrical portions and so-called slippers as additional sealing elements which give the vane a certain amount of oscillatory freedom.

This type of configuration has also been tried as a steam or internal combustion engine. Indeed a 100 B.H.P. steam version designed by A. Patschke was in production for a while at the beginning of the present century at the Wilhelmi Company of Mülheim-Ruhr. It did not appear to have the prerequisites of lasting success, however. Its internal details proved rather complex and consequently expensive to produce.

7.7 Central-axis machines

Central-axis rotating-piston machines SROM IX/17–20 (chart 9) belong to a category of SROM machines which exhibit arctuate-like engagement. This type of machine does not incorporate two axes of rotation, one beside the other, because both shafts are concentric and therefore turn about the same centre line.

Variable volume working chambers can only be formed if at least one of the rotating members moves at variable velocity. For this reason it is impossible to convert central-axis rotating-piston machines into single or planetary rotation mechanisms. Central-axis rotating-piston machines with circular-rotation characteristics cannot exist because every crank or other device facilitating this kind of circular movement presupposes two parallel axes while there is only one axis of rotation in a central-axis configuration. Nevertheless, it seems that the importance of deficiencies arising when components move at variable velocity were seriously underestimated by many inventors, scientists, engineers and manufacturers. It can only be assumed that the compactness of these machines relative to their swept volume together with the absence of any kind of valve proved the overriding attraction. Central-axis machines with straight through vanes can displace per revolution a volume which is much greater than the volume of the annular ring chamber of the particular engine. This is due to the fact that the vanes are, of course, double acting and move at variable velocities relative to each other. These features were particularly prominent on the Baradat-Esteve design of 1919 and on the Le Granjaques (1919) and Kraus (1963) configurations which relied upon oval gears to ensure their enormous volumetric throughput; as four-cycle engines they featured four complete thermodynamic cycles per shaft revolution, during which time the vanes are subjected to only two acceleration and two deceleration periods. Furthermore these advantages are also enjoyed by engines devoid of any parts moving at variable angular velocity. The sealing problems of central-axis rotating-piston machines may appear easy to solve to some, who also believe that the broad sealing bands, evident in their designs, are adequate. Despite innumerable failures it seems impossible to shake the widely held belief that good fits and close running clearances constitute a satisfactory means of sealing heat engines and rotary-piston internal combustion engines in particular. In reality differential thermal expansion demands unduly large running clearances which make this type of sealing impracticable. Furthermore, the relative disposition of the rotor and their shapes make it practically impossible to devise mechanical sealing elements which form a complete sealing grid capable of blocking every possible leakage path. Even if the significance of these problems – frequently assumed to be negligible, but actually insoluble – is overlooked, it is surprising that this 'stop-go-stop' rotation (Kauertz in 1960, for example) has found so many protagonists willing to spend considerable effort on its realisation, even among large companies. As soon as the segmental pistons of SROM machines rotate at variable velocity about their respective centres of gravity the particular machine is afflicted with all the disadvantages due to variable inertia forces, as is the reciprocating piston machine. It is, of course, quite immaterial whether stresses or bearing loads are due to linear or angular acceleration and consequential inertia variations. Hence all cross-sections must be so proportioned as to reduce the stresses to acceptable levels and the bearing areas must also be large enough to produce acceptably low bearing pressures and the transmission components must also be able to cope with these additional inertia forces. It is no mere coincidence that inventors incorporate parts which perform essentially the same functions as connecting rods in order to deal with variable inertia effects. The slide connecting rod-crank arrangement has, so far, proved far more capable of dealing with these alternating accelerations and the slowing down of masses, which cause inertia forces, than sliding blocks, rollers, curved guides, cams, oval or elliptical gears.

7.8 Arctuate engagement of oscillating-pistons or sealing components

With regard to the machines of chart 10 (PROM) X) reference is made to chart 10 (PROM) X/11 (table 24) and the machines shown in lines 1/2, 3 and 4 which were developed by Tänzler in 1937. He succeeded in developing the swinging vane type piston into a synchronising coupling link which ensures that the inner and outer ring-rotors move at uniform speed. It is, unfortunately, quite impossible to give uniform velocity to these swinging links as well. Tänzler endeavoured for several years to draw the attention of engineers to the many different types of rotary piston machines by writing papers and lecturing about them.

7.9 Engagements similar to cam engagements and oscillating piston or sealing components

A single-rotation conversion of Geiger's planetary-rotation four-stroke cycle engine of 1960 – see table 26 – is shown in XI/1 (chart 9). While too many inventors, who intend to convert rotating piston machines into engines, follow the well-trodden path of already well-known configurations, or even re-invent them, Geiger suggested an entirely new design principle which was capable of accomodating the four-stroke cycle. Because of the need to provide six apex seals on the three-flank rotor his sealing arrangement is far more complex than those of SIM or PLM $\overline{\text{(SIi)}}$ machines having a speed ratio of 2:3 and depicted in SIM IV/2 and PLM IV/5 (charts 7, 8), despite the similarity of the two machines with their arena shaped bores and their ability to accomodate the four-stroke cycle.

Simpson and Shipton's marine type steam engine of 1848 is shown diagrammatically in chart 9 XI/9 which, according to contemporary report, is said to have worked quite satisfactorily. However, the complexities of the design were such that even today it would be most difficult to devise a satisfactory sealing system. It is not surprising that no more has been heard of this engine.

A rotary-piston machine similar to a James Watt design of 1782, among others, is shown in chart 10 (SROM) XI/11. Watt had been preoccupied with rotary piston machines since 1766. Contemporary reports reveal that in 1768 he endeavoured to seal the internal vane or flap with glazing putty and similar materials but the results were not very satisfactory as the sealing substances formed themselves into little balls which prevented the necessary contact between the flap and the bore or rotor drum. In particular, success eluded James Watt partly on account of the type of mechanism he chose and partly due to the shortcomings of the machine tools of his time. Besides mentioning improvements to reciprocating piston machines in a patent specification of 1874 James Watt referred to 'Steam Wheels', meaning rotary piston machines.

Another Ramelli invention of 1588 is shown in table 26 line I No. 1, the principles of which have reappeared in various designs in the course of time. The figure shown in line I No. 3 on the same model sheet represents a product of the Turboflex Company to which Professor Stauber added a rotating water sealing ring within the working chamber, thereby creating the hybrid water-ring-pump of the Siemens Company. Despite considerable efforts by Professor Stauber and the Voith Company (Germany) it proved impossible to apply the principles to a heat-engine or a large gas-engine. Combustion turbulence tore up the water-ring surface and it proved impossible to effect complete sealing. Hence, the multi-cylinder experimental engine suffered from leakages, but even if these problems had been overcome the particular design would have been condemned by the inherent shortcomings of all PROM-configurations.

7.10 Mixed engagement (meshing) methods derived from the principles of lines VI-XII of the classification charts

Engagement methods shown in lines VI—XII (charts 7—10) are already mixed methods derived from the methods shown in lines I—V; it is obviously possible to obtain further mixed methods from the principles shown in lines VI—XII. For example, the Rotasko-compressor of the Escher-Wyss Company represents a single rotation type rotating piston machine whose engagement principles correspond to those of chart 9 SROM VI/11 and SROM XI/9. Its sealing component is housed in a parallel sided slot which is not, however, directly within the enveloping casing but in a cylindrical trunnion block which has a certain amount of rotational freedom. To be precise, control levers project sideways from the sealing component and are linked to the shaft of the rotor. This arrangement ensures that the sealing component is always radial whatever position the rotor is in.

8. Machines with rolling piston rotors

Table 27 is not a model sheet but a visual comparison of PLM- and PROM-type machines whose power transmitting parts are rolling pistons, which are rather conspicuous components. At first it seems that every configuration which is to be classified should be considered as a special case. However, four fundamental and differing principles seem to apply to the designs. The rolling piston is common to all but it is merely a detail of some of the groups without being an essential feature of these configurations.

In another group the rolling piston arrangement clearly determines the engagement method and the relative position of the particular design in the classification tables. The varying significances of particular features complicate the issue and further classification is, therefore, essential.

The rolling piston and the inner housing bore of the first planetary-rotation machine chart 8 (PLM) III/5 shown, may be smooth or it may feature suitable meshing gear teeth without altering the basis of the design. Furthermore, all variations between rolling of a smooth circular piston and rolling of external teeth of the piston engaging with the internal teeth of the bore are possible. Even part smooth rolling and part rolling in the manner of meshing gears is possible. In the absence of rolling pistons some of the machines in table 27 become single-rotation or related units; in these cases the rotors are eccentrically mounted on the main shafts which are free to revolve in fixed bearings. Consequently, machines of chart 10 (PROM) VI/6 and (PROM) VI/13 of table 27, 3rd line, become the chart 9 (SROM) VI/4 and (SROM) VI/11 machines shown in table 9. Similarly the machines designated (PROM) XI/6 and (PROM) XI/13 of table 27, 4th line, become the units (SROM) XI/4 and (SROM) XI/11 of table 9. The same applies to the designs of chart 8 (PLM) V/13 and (PLM) XI/15 table 27, 3rd column, which become single-rotation machines, that is designs similar to those which can be completely balanced. For this category of machines the rolling piston acquires merely the circular-piston shape, produced by modification of the respective single-rotation rotor.

In contrast to the above models, the development of the power-transmitting part into a rolling piston, indicated in line 2 of table 27, necessitates a modification of the designation PROM VI to PROM VI ± III.

By giving the sliding piston of a chart 10 (PROM)-VI design a concave end face instead of a convex one, so that a needle-type sealing element may be inserted, the first step has been taken towards the rolling-piston principle. A sealing element which hardly projects beyond the sliding piston contour transmits so little power that it cannot be considered a power transmitting part.

In contrast to the above, the development of power-transmitting components into rolling pistons, indicated in line 2 of table 27, necessitates a new designation; thus, chart 10 (PROM) VI becomes (PROM) VI ± III.

When the sliding piston of a (PROM) VI machine is given a concave (partly cylindrical) slot in place of a convex running surface so that it can accommodate a needle type sealing element, which is free to rotate about its longitudinal axis, the embryo of a rolling piston has thereby been created. A sealing element which barely projects beyond the sliding piston contours cannot be responsible for more than a fraction of the power transmitted and must not be confused, therefore, with the piston itself. When, however, the needle type sealing element becomes a large cylindrical component which projects more than nominally, besides transmitting a great deal or even all the power, the design must be classified as a rolling piston unit. Hence the locus of the c.g. of the rolling piston about its longitudinal axes must be considered in order to classify this configuration correctly.

These machines thereby obtain cam-engagement due to the additional freedom of rotation given to the power transmitting component; indeed, these machines have become hybrids of two engagement methods.

Cam-engagement becomes more and more pronounced because the reciprocating and slip-engagement become partly or entirely superfluous as rolling elements develop into a rolling piston which also, of course, transmits the power.

Parallel sided guide slots in which the engaging parts may slide to and fro are fundamental features of the first PROM VI machines shown in line 1, table 27. The remaining configurations of the same line still feature the parallel sided guide slots but the respective engaging components are not long slab-sided sliding parts. Instead the cylindrical components, which replaced them, perform a rolling motion and have merely a line contact with the sides of the slots; the pure reciprocating engagement has been replaced by an engagement form which is only incidentally similar to it. No kind of sliding engagement is any longer evident because no sealing component is guided linearly or slides along the stationary enveloping casing (bore).

It appears tempting to add a new line headed 'For engagement similar to reciprocating and cam engagement' to charts 7–10 but this is not justifiable for the following reasons:

The above described change over from a PROM-VI design to a needle-roller sealing element and finally to a rolling piston is gradual (as far as the classification is concerned) as indicated in line 2 or table 27. And despite a rolling piston, full reciprocating engagement may still be present.

In particular the parallel sided slots and the bore shapes of the machines shown in line 2 remain the same even when a complete change over to a rolling piston arrangement has been effected. Hence, its derivation from the machines which possess the engagement principles of group VI remains quite apparent.

It may prove far more difficult to place the machines of column 4 in line 2 of table 27, although only the parallel sided guide slots of the power transmitting parts have, in fact, been displaced. In this design the guidance function is no longer performed by the sealing component, as on the other machines of the same line, but has been assigned to a special disc which rotates with the output shaft to which it is attached. The designation of this machine could, therefore, be written VI $\pm$ III $\pm$ V because the rolling pistons are in counter engagement with the stationary walls of the working chamber housing. However, the designation VI $\pm$ II seems adequate for the purposes of correct classification and ease of reference.

It is obvious from the above that the division of rolling-piston machines into more than 12 categories is quite feasible, but this extension should only be resorted to when enforced by, for example, a new and large group of designs.

9. Conclusions

It can be concluded from the above that various mixed mechanisms may be evolved from the 12 different engagement methods elaborated in the classification. Relatively few and only exceptional configurations have, in fact, been analysed, mostly by way of examples which facilitate any particular classification with reference to types and models already described. It is, of course, quite impossible to include in this classification the unlimited differences resulting from detail design, however wide and comprehensive the fundamental classification may be. To some extent these

detail variations may be conveniently shown upon the respective model sheets, on which many more designs may appear in due course.
The number of different design configurations of rotary piston machines is inordinately large, especially since the double group of 'inclined-axis' and 'intersecting-axis' machines ought to be added to the already substantial number of parallel axis machines. Closer study will indicate to the designer that many proposals need not be considered where they have already been superseded by simpler and proved principles and models. When embarking upon the design and development of a rotary piston machine, it is of paramount importance to consider the following:

1. All moving parts should move at uniform velocity — including timing components.
2. A closed circuit sealing system, eliminating as far as possible every leakage path between rotor and housing as well as the shape and size of the unswept volume contained between the rotor and the housing.
3. The design should be capable of accommodating a favourable cycle, besides ensuring adequate valve opening periods and port crossectional areas as required for the higher speed ranges.
4. The ratio of overall bulk/displacement volume (working chamber capacity) and the power to weight ratio (lb/B. H. P.), have to be favourable.
5. The components should be strong enough to accommodate the highest pressures and speeds to which they may be subjected.
6. Feasibility of adequate cooling and lubrication.

It will be found that many rotary piston machines will prove unsatisfactory in one or more of these points and must, therefore, be excluded from the evaluation even if they contain other very attractive features.
This classification of rotary piston machines should not appear without remembering the great dynamist Franz Reuleaux, 1829—1905, who attempted nearly 90 years ago in 1875 to bring order into the chaos of the rotary piston machine field which he described in great detail in his books and writings. His proposed classification was, however, a little too artificial for the purpose of imparting to the designer the characteristics of a multitude of differing machines. Later publications were neither as methodical nor as comprehensive as Reuleaux's effort and confusion prevailed. Reuleaux had apparently read all he could about the unsuccessful rotary piston heat engines which had been proposed during the preceding 150 years not only by inventors but also by otherwise successful technicians and manufacturers.
The invention of the steam-turbine and the electric generator and later the appearance of the motor car gave a new impetus to the desire to replace at least partly the reciprocating piston arrangement, but all efforts proved unsuccessful.
Exaggerated and technically inaccurate announcements sometimes preceded the actual showing of these machines, although they proved hardly capable of performing as well as the more conventional machines they were meant to supersede. An atmosphere of suspicion was thereby created so that any project to do away with reciprocating motions and components had to be pursued in secrecy if it was

not to invite ridicule. The situation was somewhat similar to that which preceded the successful invention of the aeroplane.

Reuleaux behaved in exactly the same way as many engineers did between 1850 and 1950. Lack of success and certain side effects defeated him. Nevertheless, he returned time and again to rotary-piston machines. He had encouraged Otto and Langen in their efforts to develop their atmospheric engines and assisted them right up to the discovery of the four-stroke-cycle. His technical vision is reflected in his books although they also reflected the low standard of knowledge of rotary piston design principles which prevailed. He added, for instance, a footnote pointing out that his book about the theory of dynamics was not intended to be a history of rotary steam engines and pumps. However, his book included so many examples and illustrations that it remained for decades the best known scientific review and collection of this type of machine.

Reuleaux attempted with his book an 'Analytical Geometry' to prove to himself and others the impracticability of rotary steam engines. He thereby became so involved in the terms 'Hemmwerk' and 'Laufwerk' (Braking and Power Transmitting Devices), which he himself had formulated, that he stated that rotating or planetary-rotating machines which incorporated cranks were no more rotary designs than the reciprocating piston engine itself!

In his 'Theory of Dynamics' he devoted considerable attention to the Pappenheim single-rotation machine which possesses uniform velocity; he even advocated its use in the form of gear-pumps for liquids and gases and pointed out that they could be used as engines if actuated by pressurised water or steam, as well as for other applications. He criticised the unsatisfactory sealing arrangements of the very similar steam engine design proposed by Murdock and of the much modified steam engine by Behrens. Today we know that satisfactory linear sealing systems may be devised for these designs but in those days nothing was known about the sealing of rotary-piston internal combustion engines (with the exception of ordinary reciprocating piston engines without rotary valve).

Confusion about the sealing techniques of components which are in sliding contact with each other is perhaps as persistent as lack of knowledge and faulty opinions on the principles of rotary piston machines. This lack of scientific and technical background about sealing of components with relative sliding motion had already retarded, in some respects, the development of the reciprocating internal combustion engine, while in the rotary-piston engine field it militated against proper functioning altogether, since even quite suitable designs presented leakage problems. The development of the rotary-piston machine into a high performance internal combustion engine was facilitated by more than 30 years work on sealing systems and after many different engine configurations had been evalued, developed or invented.

Various design studies assisted in bridging the gaps between different types of rotary combustion engines during this preparatory period. Simultaneously with this, the classification became the instrument which determined more and more precisely the correct relative position of each individual design within the multitudes of rotary-piston machines. A valuable perspective was thereby obtained of these complex designs, facilitating their appraisal, their relative evaluation and exploitation. Many other configurations will probably spring from this work for later classification. Already this classification contains gear-type pumps and rotary blowers and compressors besides single and planetary-rotation four-stroke cycle engines.

Index for tables

Glossary

Definitions of reciprocating-engagement $\overline{(R)}$, arctuate-engagement $\overline{(A)}$, cam-engagement $\overline{(C)}$, slip-engagement $\overline{(Sl)}$, counter engagement of internal $\overline{(Co)}$ and external-axis ROPIMA.

I. Reciprocating-engagement $\overline{(R)}$: exclusively linear motion of engaging components.

II. Arctuate-engagement $\overline{(A)}$: engaging components move in parallel circular arcs. The engaging parts have equal/unequal diameters but possess equal r.p.m.[1] and equal number[2] of teeth.

III. Cam-engagement $\overline{(C)}$: rotation in same direction – in manner of engaging gears.

a) Internal-axis machines:
The engaging component with the small diameter and higher r.p.m.[1] has fewer teeth[2]. The engaging part with larger diameter and lower r.p.m.[1] has a greater number of teeth[2]. Engaging components possessing equal diameters and equal r.p.m. have equal numbers of teeth; they belong to category II; arctuate-engagement M/C.

b) External-axis machines:
The engaging-component with equal/smaller diameter and higher r.p.m.[1] has few[2] teeth. The engaging-component with equal/unequal diameter and lower r.p.m.[1] possesses a larger number[2] of teeth.
The engaging-component with equal/unequal diameters and equal r.p.m.[1] possess equal numbers[2] of teeth.

IV. Slip-engagement $\overline{(Sli)}$ or $\overline{(Sle)}$: direction of rotation at contact point in same direction i.e. like rolling parts.

a) Internal-axis machines:
Engaging components with larger diameter and higher r.p.m.[1] possesses fewer[2] teeth. Engaging component with smaller diameter and lower r.p.m.[1] possesses more[2] teeth.

b) External-axis machines:
Slip-engagement cannot be separated from cam engagement.

V. Counter-engagement $\overline{(Coi)}$ or $\overline{(Coe)}$: direction of rotation at engaging point in opposite direction.

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[1] When an engaging component is at rest its notation is transferred to the crank-pin.
[2] The term teeth is used in a broad sense and means lobes, projections etc. of components performing an engagement function.

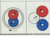
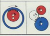
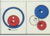
Significance of the colour code

- (red) Piston-runner or rotor (output component)
- (blue) Sealing-rotor (sealing component)
- (magenta / purple) Alternating or simultaneous piston or rotor and sealing component
- (black) Stationary chamber wall
- (yellow) Crank
- (green) Sealing element

Illustrations of engagement methods

Internal-axis SIM

Similar arrangement to the axes of an external-tooth gear meshing with internal tooth ring gear

Principle of Engagement	I. Reciprocating engagement (R)	II. Arctuate engagement (A)	III. Cam engagement (Ce) or (Ci)	IV. Slip engagement (S)	V. Counter engagement (Coi) or (Coe)
Example of models	Inpossible as SIM machines				
Diagrammatic sketch, arrows indicate direction of rotation					
Distinguishing mark		At point of contact the rotating parts move in same direction. Engaging parts pursue parallel circular paths. They revolve at equal r. p. m.	At point of contact motion is in same direction. Engaging component with smaller diameter and higher speed has fewer teeth. Larger diameter part running at lower speed has more teeth.	At contact point rotation in same direction. Larger diameter part with higher speed has fewer teeth. Smaller diameter part with lower speed has more teeth.	Direction of rotation at contact point in opposite direction. Speed ratio may be anything provided it is a whole number.
Gear connections between axes					

3 External-axis SIM

Similar to the axes of a pair of meshing spur gears

Principle of Engagement	I. Reciprocating engagement (R)	II. Arctuate engagement (A)	III. Cam engagement (Ci) or (Ce)	IV. Slip engagement (S)	V. Counter engagement (Coi) or (Coe)
Example of models	Impossible as SIM machines	Impossible with external-axis SIM machines		Cam engagement cannot form chambers on external-axis machines.	
Diagrammatic sketch, arrows indicate direction of rotation					
Distinguishing mark			At contact point rotation in same direction. Component with equal or unequal diameter and higher speed has fewer teeth. Component with equal or unequal diameter and lower speed has more teeth. Component with equal or unequal diameter and equal speed has equal number of teeth.		Direction of rotation at contact point in opposite direction. Speed ratio may be anything provided it is a whole number.
Gear connections between axes					

4 Internal-axis PLM

Internal-axis PLM with inner piston-rotor similar to the arrangement of axes of pinion and internal-tooth ring gear, the piston-rotor revolving about its own centre of gravity

Principle of Engagement	I. Reciprocating engagement (R)	II. Arctuate engagement (A)	III. Cam engagement (Ci) or (Ce)	IV. Slip engagement (S)	V. Counter engagement (Coi) or (Coe)
Example of models					 Sealing component if present = crank
Diagrammatic sketch, arrows indicate direction of rotation					
Distinguishing mark	Linear motion between the engaging components. Piston-rotor rotates in opposite direction to crank at half crank speed relative to housing. Sealing component also rotates in same direction at half crank speed relative to casing.	Circular parallel motion of the engaging components. Piston-rotor revolves in opposite direction to crank but at the same speed as the crank relative to the casing.	Rolling motion at engagement point. Piston-rotor revolves in opposite direction to crank but at higher speed than the crank relative to casing. Engaging component with smaller diameter and higher speed has smaller number of teeth. Engaging component with larger diameter has more teeth.	Rolling motion at engaging point. Piston-rotor revolves in opposite direction to crank but at lower speed relative to casing. Engaging component with larger diameter has fewer teeth. Engaging component with smaller diameter and lower speed has more teeth.	Counter movement at point of contact. Piston-rotor revolves at equal speed round crank pin at any speed ratio to crank relative to casing provided it is a whole number.
Gear connections between axes			 	 	

Internal-axis PLM with outer piston-rotor similar to the arrangement of axes of ~~pinion~~ and internal tooth ring gear, piston-rotor rotating about its own centre of gravity

5

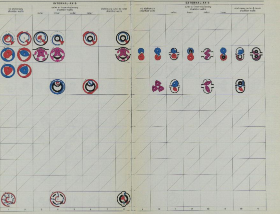
Principle of Engagement	I. Reciprocating engagement (R)	II. Arctuate engagement (A)	III. Cam engagement (Ci) or (Ce)	IV. Slip engagement (S)	V. Counter engagement (Coi) or (Coe)
Example of models					
Diagrammatic sketch, arrows indicate direction of rotation					
Distinguishing mark	Linear motion between the engaging components. Piston-rotor rotates in opposite direction to crank at half crank speed relative to housing. Sealing component also rotates in same direction at half crank speed relative to casing.	Circular parallel motion of the engaging components. Piston-rotor revolves in opposite direction to crank but at the same speed as the crank relative to the casing.	Rolling motion at engagement point. Piston-rotor revolves in opposite direction to crank at lower speed than the crank relative to casing. Engaging component with smaller diameter has fewer teeth. Larger diameter part with lower speed has more teeth.	Rolling motion at engagement point. Piston-rotor revolves in opposite direction to crank at higher speed relative to casing. Engaging component with larger diameter and higher speed has fewer teeth. Larger diameter part has more teeth.	Counter movement at point of contact. Piston-rotor revolves at equal speed round crank pin at any speed ratio to crank relative to casing provided it is a whole number.
Gear connections between axes					

External-axis PLM have axes similarly arranged to meshing spur gears and the rotating piston-rotor revolves round its c.g. which itself follows a circular path

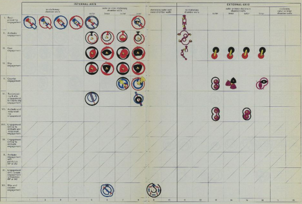
6

Principle of Engagement	I. Reciprocating engagement (R)	II. Arctuate engagement (A)	III. Cam engagement (Ci) or (Ce)	IV. Slip engagement (S)	V. Counter engagement (Coi) or (Coe)
Example of models			 Sealing component if present = crank	Cam engagement cannot form chambers on external-axis machines.	 Sealing component if present = crank
Diagrammatic sketch, arrows indicate direction of rotation					
Distinguishing mark	Linear motion of engaging components. Piston-rotor revolves in opposite direction to crank and at the same speed relative to the casing. Crankshafts rotate in opposite directions.	Circular parallel motion of the engaging components. Piston-rotor revolves in opposite direction to crank and at the same speed relative to casing. Crankshafts rotate in the same direction.	Rolling motion at engaging point. Piston-rotor revolves in the same direction relative to housing. Engaging component with equal or unequal diameters and higher speeds have fewer teeth. Engaging component with equal or unequal diameters and lower speeds have more teeth. Engaging component with equal or unequal diameters have equal number of teeth.		Counter rolling movement at contact point. Piston-rotor revolves in opposite direction to crank pin at any speed ratio relative to crank, provided it is a whole number.
Gear connections between axes					

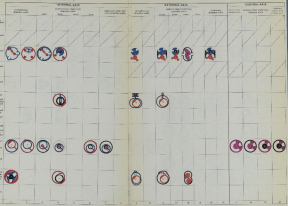
7 Classification of single-rotation machines (SIM)



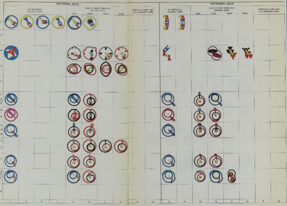
8 Classification of planetary-rotation machines (PLM)



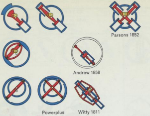
9 Classification of single-rotation rotating-piston machines (SROM)



10 Classification of rotating-piston machines with engagement similar to arcuate engagement (PROM)

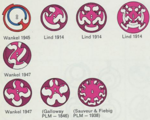


11 Model Sheet



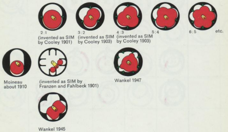
Types of internal-axis machines PLM (R) Chart 8 I/1

12 Model Sheet



Types of internal-axis machines SIM (A) Chart 7 II/2

13 Model Sheet

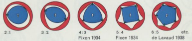


Types of internal-axis PLM (Ce) Chart 8 (PLM) III/7

Model Sheet **14**

Types of internal-axis PLM (Ci) Group PLM III/5

Model Sheet **15**



Types of internal-axis SIM (Ci) Group SIM III/2

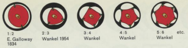
Model Sheet **16**

Types of internal-axis PLM (Sle) Group PLM IV/7

Model Sheet **17**

Types of internal-axis SIM (Sli) Group SIM IV/2

18 Model Sheet

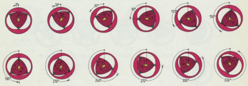


Types of internal-axis PLM (S̅l̅i̅) Group PLM IV/5

19 Model Sheet

Types of internal-axis PLM (S̅+̅R̅) Group PLM VI/5

20 Phasing Diagram



Diagrammatic arrangement of relative rotor positions of 2:3 machine, outer rotor has additional PLM rotation

Special Sheet 21

Internal-axis PLM (Sli) IV Slip-engagement 2 : 3 | Internal-axis PLM (Sle) III Cam-engagement 3 : 2 | Dillenberg 1961 Internal-axis PROM IX Arctuate-engagement

Internal-axis PLM (Sle) III Cam-engagement 2 : 1 | Internal-axis PLM (Sle) III Cam-engagement 2 : 1

ROPIMA machines with additional motion which is not required

Model Sheet 22

Ramelli 1588 | Wittig about 1900

Emery 1869 | Davies 1867 | Jones & Shirreff 1856

Types of internal-axis PROM machines Group PROM VI/5

Model Sheet 23

Trotter 1805 | Cochrane 1830 | Fletcher 1843

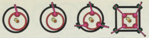
Types of internal-axis SROM machines Group SROM IX/3

Model Sheet 24

Tänzler 1937 | Tänzler 1937 | Tänzler

Types of external-axis PROM machines Group PROM X/11

25 **Model Sheet**



Types of internal-axis PROM machines Group PROM X/5

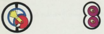
26 **Model Sheet**

Ramelli 1588 | Cochrane | Turboflex

Geiger 1960 | Sugopump

Types of internal-axis PROM machines Group PROM XI/5

27 **Sheet of Comparisons**



PLM III/5 | PLM V/13

PROM VI+III | PROM VI+III | PROM VI+III | PROM VI+III

PROM VI/6 | PROM VI/13

PROM XI/6 | PROM XI/13 | PROM XI/15

PLM and PROM machines with rolling-piston rotor

Special Terms and Expressions Used in Conjunction with Rotary Piston Machines

HKM = Hubkolbenmaschine	REM = reciprocating-piston machine
RKM = Rotationskolbenmaschine	ROPIMA = Rotary piston machine
DKM = D = Drehkolbenmaschine	SIM = Single rotation machine
KKM = K = Kreiskolbenmaschine	PLM = planetary-rotation machine
UKM = Umlaufkolbenmaschine	ROM = Rotating-piston machine
DU = Drehkolbenartige Umlaufkolben-Maschine	SROM = Rotating-piston machine similar to single-rotation machine
KU = Kreiskolbenartige Umlaufkolben-Maschine	PROM = Rotating-piston machine similar to planetary-rotation machine
(K) = Kammeingriff	(C) = Cam engagement (or meshing)
(S) = Schlupfeingriff	(Sl) = slip engagement (or meshing)
(KR) = Kreiseingriff	(A) = arctuate engagement (in circular arc)
(G) = Gegeneingriff	(Co) = counter engagement
(H) = Hubeingriff	(R) = reciprocating engagement
* Parallelachsige RKM	ROPIMA machines with parallel axes
* Parallel-außenachsige RKM	ROPIMA machines with external axes
* Parallel-innenachsige RKM	ROPIMA machines with internal axes
* Mittelachsige Maschinen	Central axis machines
* Winkelachsige Maschinen	Machines with axes inclined towards each other
* Winkel-außenachsige Maschinen	Machines with external axes inclined
* Winkel-innenachsige Maschinen	Machines with internal axes inclined
* Geschränktachsige RKM	ROPIMA intersecting or crossed axis machine
* Geschränkt-außenachsige RKM	ROPIMA intersecting external axis machine
* Geschränkt-innenachsige RKM	ROPIMA intersecting internal axis machine
Bauarten	types
Bauformen	models, versions
Schwerpunktverhalten	behaviour of the centre of gravity
Kolbenlaufer KL	RP = runner, rotor, rotating piston
Schwingbaum	rocking beam or swinging beam
Wagnerscher Hammer	electric bell actuating device said to have been invented by: John Maraud (E) J. P. Wagner (G) Neff (F) Page (USA)
Absperrteil = AL	SC = Sealing or containing components, not sealing element
Einteilungs- oder Systemblatt	classification chart
Umlaufkolben-Sternflugmotor	radial aircraft engine, Gnôme le Rhône
Kurvenerzeugungspunkte	curve generating points
Verzahnungskörper	(tooth) generating part or body
Paarkolben	double, double acting or pair of pistons
Paarflügelkolben	single vane right through rotor
Paarschieber	sliding vane valve
Eingriffskörper	catch, pawl, engating or meshing
Arenakurven	oval track shaped like circus arena
Schädlicher Raum	Volume contained at TDC
Kardenkreisgesetz	Principle of HYPOCYCLOID (R = 2 r)
Kardankreisgetriebe	Epicyclic or planetary gearbox
Querzylindrisch	Cylinder transverse or parallel to axis of rotation
Ovalzahnräder	Oval gears (used in counting machines)

Schubkurbeltriebwerk	Slide and crank mechanism
Synchronkoppelglied	Coupling link of or for synchroniser
Schenkwinkel	Angle of obliquity Angle of incident Leaning angle of apex seal relative to normal to bore
Laufdichtfläche	Primary or sliding seal area (high relative velocity)
Rutschdichtfläche	Secondary or drift seal (side of sealing element where there is only nominal movement)
Dichtbolzen	Sealing block, link-block of Wankel sealing grid
Dichtgrenze	Sealing boundary where sealing ends, occurs, is effected, **sealing grid**
Zweimaschinensatz	Machine consisting of two units, compression and expansion units
Zellenräder	Multi-vane rotors, pumps or compressors

* Most complicated, difficult to draw. not elaborated on in book

Index

(Prefix T indicates table number)

Wankel
Rotary piston machines.