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In the field of electrical engineering the constant speed electric motor soon superseded the reciprocating motor which had been derived from coil type bell actuating devices variously said to have been invented by John Maraud, J. P. Wagner, Neff or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 towhich 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 $\overline{(C)}$ * 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 $\overline{(S)}$.
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.

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* 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 (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 (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 (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 $\overline{(Ce)}$; 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.