A SURVEY OF ROTARY TYPE INTERNAL COMBUSTION
ENGINES WITH PARTICULAR EMPHASIS
ON THE N.S.U.-WANKEL ENGINE

by

HIRIYUR VEERANNA CHANDRASHEKAR

B. S., Mysore University, India, 1958

———————————

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

Approved by:

Major Professor

TABLE OF CONTENTS

NOMENCLATURE

e = eccentricity

G = center of gravity

h = thickness

N = rotational speed

p_{me} = mean effective pressure

P = output

r = pitch circle radius

R = generating radius

V_c = volume of the chamber

ξ = compression ratio

$\measuredangle$ = angle of obliquity

β = angle described by the line passing through the point of contact of the meshing gears and the center of the circular hole in the rotor, with reference to a fixed axis

θ = angle of inclination of the line joining the center of the stator and the centroid of the rotor to the x-axis

$\emptyset$ = leaning angle

INTRODUCTION

The conventional reciprocating internal combustion engine suffers from several fundamental shortcomings. A major loss of power occurs during the conversion of linear reciprocating motion into rotary movement. Undesirable vibrations are caused due to the nonuniform torque. There is a basic mechanical and thermal limitation imposed on the power-plant ratio. The piston rings will seize and the valves will burn on stepping up the thermal loading. At high rates of revolution under inertia forces, valve gears and other reciprocating parts may fail to operate. The operational speed is limited by the stresses developed due to the reciprocating motion. Despite these defects this engine has been reigning in the automotive field for eighty-odd years.

The idea of doing away with reciprocating motion is not new. The first applications of the rotary principle can be traced back to James Watt and his co-worker Murdock. Other famous engineers like James Ericson, Westinghouse, de Laval, and Parsons worked on rotary engines. None of their designs, however, were successful, largely because the sealing problem could not be solved with the scant knowledge and means available at that time.

Of late the supremacy of the time-proved engine has been seriously challenged by a number of positive displacement rotary engines. Various solutions have been suggested to the problem of sealing. Quite a few of the engines are of academic interest

only; many practical considerations are overlooked. Several designs are just experimental curiosities, but it was from an experimental curiosity that the reciprocating engine had its beginning. Some of the engines have been built and tested; the results are encouraging and are worthy of serious consideration.

In view of the merits and disadvantages of the proposed engines, the N.S.U.-Wankel engine seems to be more promising than others. This has all the appearances of being a revolutionary design and there is an impressive list of favorable points to its credit. The inventor has taken from the reciprocating piston engine only the system of introduction of fuel and the ignition system based on the four-cycle principle. This is also comparable to a turbine, since it possesses no parts which operate in reciprocal motion. Thus the N.S.U.-Wankel engine may be labeled a hybrid engine which is a result of a cross between an orthodox reciprocating engine and a modern reaction turbine.

Curtiss-Wright Corporation, Wright Aeronautical Division, Wood-Ridge, New Jersey, and N.S.U., Notorenwerye, A.G., Germany, are working on the design and development of this engine.

In this report the designs proposed by a host of inventors have been analyzed to point out certain advantages and disadvantages. Also, a particular design of the N.S.U.-Wankel engine is developed in order to show the design procedure and associated problems.

REVIEW OF LITERATURE

Men of both academic and practical fields are always look-
ing for alternatives in engine design to compete with the com-
mercial reciprocating engine. Many alternatives have been
suggested and some show good merit.

E. S. Starkman, of the University of California (17), has
expressed his opinion that the conventional spark-ignition engine
appears to be reaching an impasse in its development. Increases
in economy and performance are becoming more and more difficult
and costly to attain. And the most direct way to improvement--
to raise the compression ratio--is becoming limited by:

1. Our lack of knowledge of how to control the rate of
pressure rise so as to avoid such undesirable phenomenon as
rumble. (Present designs can tolerate a rate of pressure rise
of only 25 psi per degree without rumble occurring.)

2. Optimum performance occurring unexpectedly at only 17
to 1 compression ratio in multicylinder engines operated in
the laboratory.

Thus there appears to be little likelihood of a general
widespread increase in compression ratio in the foreseeable
future and so other configurations, such as the stratified-
charge engine, the gas turbine, the free piston engine, the
Wankel rotating combustion engine, and direct energy conversion
devices are beginning to look worthy of serious consideration.

Julius E. Witzky, of the Automotive Research Department,
Southwest Research Institute, San Antonio, Texas (19), remarks

that in spite of the fact that the internal combustion engine
has been in development for many decades, the battle for the
B.t.u. is still in progress. Every new prime mover goes through
this battle to improve its thermal efficiency because history
teaches us that the machine with a higher thermal efficiency
will replace the engine with a lower thermal efficiency.

Where fuel and air consumption are of importance, the diesel
engine will prevail; where size and weight are prime, the gas
turbine will be chosen. For passenger cars, the time-proved
reciprocating gasoline engine will be with us for a long time
to come. However, the compact and lighter N.S.U.-Wankel engine
is certainly a strong contender, esepcially for the small,
European-size car.

The gas turbine has some outstanding characteristics and
an impressive list of good points in its favor. It has only
about a fifth as many parts as a comparable reciprocating
engine. It is a truly multi-fuel engine and runs happily on
all hydrocarbon fuels ranging from diesel fuel at one end of
the scale to high-octane motor gasoline at the other end of the
scale. It has already proved its reliability and will start
easily at low temperature. The fascinating torque curve makes
the turbine look like an appealing power plant for vehicle
application, easing the transmission problem and providing a
smooth flow or torque to the drive shaft. One of the major
drawbacks is the high fuel consumption and the large air quantity
which has to be handled. The acceleration is very slow, which
accounts for the reason that in spite of the excellent torque

characteristics, a transmission is necessary for the vehicles. Trucks, buses, earth-moving, and military combat vehicles and similar applications, where a much higher load factor is usually required, are more suitable for gas turbine application than passenger cars.

The designs proposed by a number of inventors can be broadly classified into the following groups:

1. Rotary piston engines
2. Rotary cylinder engines
3. Vane-type engines
4. 'Cat-and-mouse' engines.

Rotary Piston Engines

A rotary piston engine invented by Walter Clark Dean (18), a student member of the American Society of Mechanical Engineers, who won the Old Guard Prize for 1963, is of ingenious design. The engine consists of three main rotors--a large central rotor and two small rotors. The small rotors are one-half the size of the large rotor so that they rotate twice as fast as the larger. The upper rotor and the chamber therein is called the transfer rotor, and the lower rotor the intake and exhaust port rotor, or simply the port rotor. There are two large teeth on the central rotor. These teeth are the working elements of this engine as the piston is the main working element of the reciprocating engine. These teeth seal on the housing at the tip of each tooth. A seal at the point of rolling contact

between the primary rotor and the two small rotors is effected
by gearing the three rotors together in contact with a large
number of small involute spur gear teeth.

Some of the advantages of this engine's unique configura-
tion are: All shapes are easy to machine, the driving teeth
are standard epicyclic shapes, and the housing with the three
rotors are all circles. An interesting characteristic is that
there is a constant moment arm on which the gas pressures act
to develop the engine's torque. The result is that the torque
is directly proportional to the sum of the pressures acting on
the faces of the two drive teeth. In the reciprocating engine
the moment arm is minimum when the pressure is maximum so that
the engine cannot utilize this maximum pressure in developing
torque, but this engine utilizes this maximum pressure.

Probably the most useful feature of this engine is the
fact that there is a large amount of space within the central
rotor that has no function in the operation of the engine.
Since every power source must be coupled with some device that
is to do useful work, the space within this engine is ideally
suited to being a location for the useful work mechanism. A
transmission could be located in this space, or a torque con-
verter, a pump, a generator, a fan for cooling the engine, or
almost any unit that would ordinarily require extra space in
the vicinity of the engine. As admitted by the inventor, at
present, this engine is just an experimental curiosity. If a
satisfactory solution for the sealing problem is found, this
promises a new era in high thermal efficiency of the internal

combustion engine.

R. F. Ansdale (6) is of the opinion that any rotary pump or blower can, in principle, be converted into an internal combustion engine. A design proposed in Great Britain consists of a combustion chamber bolted to a Roots blower which is used as a motor. A spark plug or glow plug is fitted to the combustion chamber. Simplicity is claimed to be the salient feature of this engine. But the difficulty of sealing is very acute. Even under favorable conditions, the thermal efficiency could hardly exceed four per cent.

H. S. Gilbert (6) has built an engine without any compression phase. This consists of three moving parts: A main rotor with two vanes and two diametrically opposed rotary elements for sealing the inlet from the exhaust and which have cut-outs designed to allow the vanes to pass. Two simple combustion chambers are attached one to each inlet duct. The drawbacks of this engine are unsatisfactory sealing and low maximum thermal efficiency, as low as five per cent.

Ferdinand Unsin (6) has invented an engine consisting of two rotors, one having a projected tooth and the other having a suitable depression to have frictional contact. A rotary inlet valve admits the mixture into the cylinder. The sealing elements are accommodated in the casing. No spark plug is indicated in the design. Small engines may not require a compression phase. But for bigger engines, external combustion may be necessary.

Walter Scheffel (6) has designed an engine based upon the

well known principle that oval or elliptical rotors can be designed to maintain constant contact while turning about fixed centers. Three or more rotors can be run, with constant minimum clearances between them, so that the volume that they enclose varies continuously. Hence it is only a question of arranging the porting and ignition and designing for adequate compression ratios to convert this type of blower or pump into an internal combustion engine. Nine rotors are employed in the Scheffel engine. Complexity is the most unfavorable point of this engine. The rotors must turn in the same direction which is contrary to the sense of motion of a pair meshing gears.

Helmuth Walter (6), the originator of the Walter rocket motor, has invented an engine based upon the interaction of elliptical rotors. Combustion takes place at constant volume and the compression ratio depends principally on the size and form of the large rotor. The torsional vibrations are minimized and cooling arrangements are satisfactory. The design is realistic and of some interest.

Thomas (8) of the U.S.A., has proposed an engine which has a four-lobe cylinder bore and a five-lobe rotor. There are two inlet and exhaust ports and two sparking plugs, one of each for each thermodynamic cycle. Hence the respective ports and sparking plugs are diametrically opposite one another. As a result, there are ten complete thermodynamic cycles for every 360 degrees of rotor movement, and the speed of the output shaft is five times that of the rotor. This engine is of considerable interest.

Angelo Renato Ferro (8), of Italy, has patented a design in which the rotor of the engine is guided along its orbital path by three equally spaced rollers extending right through it, to follow epitrochoidal paths in the two end covers. Power is transmitted from the rotor to the output shaft by way of an internal gear which is integral with or attached to the rotor, and a straight spur gear which forms part of the output shaft. Lack of simplicity is the most unfavorable point of this engine.

An entirely different configuration of epitrochoidal rotary combustion engine, having a ratio of 3:4, is incorporated in the Spand two-stroke engine (8). This unit consists of a three-lobe rotor and a housing having a four-lobe bore, giving twelve combustion phases per revolution of the rotor. The individual chambers are separated from each other by four stationary sealing strips which are continuously in frictional contact with the main rotor. The rotor turns about its own center which coincides with that of the crank throw. At the same time it performs a planetary motion around the axis of the main shaft. A central square-shaped stator is housed within the main rotor but is anchored to one of the end covers so that each of its corners traces, relative to the rotating component, a locus parallel to the contours of the outer or main rotor. Thus the volumes of the inner chambers vary and this is used to promote the scavenging of the actual combustion chambers. Mixture or air enters the inner chambers by way of the hollow main shaft and flows through transfer ports into the combustion chambers, as in most conventional two-stroke engines. Although the configuration of

this engine does not seem to satisfy all the requirements of a
successful rotary combustion unit, there is no basic reason why
the deficiencies should prove insuperable.

James W. Marshall and his company, Compressors and Engines,
Ltd., England, have been working on a unit known as turbo-
radial engine (3). The turbo-radial two- and four-cycle, single
and double rotary engines belong to the family of epicycloidal
trochoids. The combustion chambers are of compact spherical
segment shape and a large number of ignitions may be arranged
within a single rotor chamber and the spark plugs are fully
cooled by the incoming charge. There are three lobes to the
rotor which moves within a casing having four combustion chambers.
Hence the relationship for this engine is three to four. The
engine fires four times per revolution of the driving shaft in
two-cycle form and two times in the four-cycle form. The gas
seals are stationary and positioned in the rotor casing. These
seals, therefore, are not subjected to centrifugal, centripetal,
tangential, and inertia loads and the very light spring pressure
required to keep these seals always in contact with the rotor
periphery is the same regardless of engine speed. This means
the very minimum possible friction and perfect sealing at all
speeds. This engine is a symmetrical radio engine so that the
casing expands uniformly and is not subjected to heat distortion.
The designers claim that the engine is extremely simple and
very cheap to produce in multi-ignition form. This interesting
design is of great promise.

Rotary Cylinder Engines

Engines in which the cylinders rotate and the crank shaft is stationary have been used in a few cars, but mainly in aircraft. This type was originated by F. O. Farwell in 1898 and it was first produced commercially in 1903, when it powered a passenger car manufactured by the Adam Company, of Dubuque. Although this vehicle was in production for a number of years, it did not achieve lasting success.

The rotary principle has been revived but in a different sense with the Selwood orbital engine (4). This 12-cylinder, two-stroke engine designed and built by William R. Selwood, Ltd., of Chandler's Ford, Southampton, has arrested the attention of automotive engineers. The basis of the Selwood engine is a kinematic inversion of the swash-plate system which is usually employed in hydraulic pumps and motors. Both the cylinder and piston rotate about a stationary shaft. The reciprocating motion of the piston in the cylinder is only relative but not absolute, as they simply orbit about an axis set at an angle relative to the axis of rotation of the cylinder block. Consequently the inertia forces of the traditional engine do not come into play. Because of the absence of the connecting rods, frictional losses are low. It is said (11) that in this unusual rotary cylinder engine the thermodynamic efficiency of the conventional piston engine is combined with the low stresses and friction losses of a gas turbine. The advantages claimed for this ingenious design are perfect balance, uniform torque, low

mechanical stresses, less frictional losses, compactness, and low weight in relation to the swept volume. One of the objections leveled against this engine is that only a small component of the piston thrust can apply an actual turning moment, resulting in lower mechanical efficiency than that of the conventional engine. Another point on the discredit side is that it is expensive to machine the bores of cylinders with part toroidal than with straight axes.

In the Granville Bradshaw's Omega engine (6), the housing rotates to time the opening of the ports, but the pistons themselves oscillate in the toroidal bore. It is claimed by the designers that this very compact unit has a high specific power output and good fuel consumption. The disadvantages of this engine are that this arrangement of piston and cylinder presents peculiar production problems and the differential thermal expansion could be serious.

Vane-type Engines

Vane-type pumps and blowers have been modified to work as internal combustion engines.

The Rotom engine (7), an adoption of the vane-type pump, is a four-stroke engine having an oval bore containing a rotor with six equally spaced sliding vanes. The induction, compression, expansion, and exhaust are spaced in different annular segments. An unusual feature is that the two-piece vanes are guided along the entire lengths of their ends in the end

flanges of the rotor. Additional guidance is afforded by slots in the rotor drum, as is customary with vane-type pumps and blowers. It is claimed that this method of guiding vanes has solved the end-sealing problem. Other salient features of this engine are air cooling of the engine and the novel backflash ignition system. The lubrication, sealing, and wear problems are severe.

Paul Deville and Guy Negre (7) have built another vane-type engine. The principle of this engine is simply reliance upon a single rotor and three spring-loaded sliding vanes resting in a two-lobe bore. There are two variable volume chambers, two inlet and exhaust ports, and two sparking plugs. An unusual feature of this engine is that it does not have a compression phase in its cycle. Although the expansion ratio is therefore relatively large and exhaust temperature low, the mean effective pressure figures undoubtedly will also be disappointingly low and the amount of useful work of which this engine is capable will be correspondingly small. An internal combustion engine having no compression phase or compressor is most unlikely to show a thermodynamic efficiency in excess of three to five per cent.

'Cat-and-mouse' Engines

In the cat-and-mouse engines (6), the pistons orbit in an annular cylinder, that is, about the center around which the axis of the annular cylinder is described. To vary the volume

of the chambers, and thus to perform the compression and firing functions, some of the pistons have to orbit at varying velocities. Generally one piston of each pair continuously approaches and recedes from the other, and it is from this continuously approaching and receding motion, which is comparable to the manner in which a cat chases a mouse, that the name is derived.

T. Tschudi, Eugen Kauertz, Hans Fritz, Maier, J. C. Rayment have designed engines based on this principle. A point on the credit side of these engines is the remarkably favorable relationship between the swept volume and the overall bulk of the engine, an advantage which is not peculiar to this configuration. But the inertia effects of the piston's orbiting at varying speeds about a common center impose the same disadvantages and limitations as the inertia forces of the reciprocating masses do in the conventional piston engines. Running clearances are liable to alter as a result of thermal expansion of the rotor and housing. The sealing of the joint between the segmental pistons and supporting flanges is very difficult. The cooling of the pistons is another problem. Due to the machining difficulties the cost of manufacture may be prohibitive.

It is neither necessary nor possible to review all the rotary engines proposed by various designers. This survey, comprehensive though not exhaustive, reveals the fact that there are a number of possibilities for the design of a positive displacement rotary engine. These engines are not based on any new thermodynamic principle or theory. The ingenuity of the designers

lies in the brilliance of the general conception and detail design of the components.

N.S.U.-WANKEL ENGINE

The engine known as the N.S.U.-Wankel engine is the outcome of research for over three decades of Felix Wankel, a practical German engineer. In 1926, Wankel started exploring the possibility of a positive displacement rotary engine and by 1951 he was able to arrive at some conclusions. He concluded (14) that three main problems had prevented the rotating engine from achieving success so far.

1. The multiplicity of possibilities of arrangements and cycles for rotary engines which almost overwhelmed the inventors.

2. The problem of sealing high pressure chambers. This involved not the simple task of sealing a circular cylinder, but the more complex problem of sealing in several planes, with the sealing of corners as the most difficult.

3. The problem of developing a proper thermodynamic and gas cycle with adequate port areas and timing of events.

The combination of a suitable geometric and kinematic arrangement which offered good sealing possibilities, and could incorporate an efficient cycle within one engine, had to be found. Wankel eventually arrived at two rotary combustion engine configurations which appeared superior and were

subsequently built and operated satisfactorily.

In both the configurations the engine has two main components, an outer rotor having a cavity within which an inner rotor is relatively rotable. In practice the outer rotor preferably consists of a center housing and two attached side housings. The two rotors have spaced but parallel axes. The inner surface of the center housing is an epitrochoid while the outer surface of the inner rotor approximates the inner envelope of this epitrochoid during their relative rotation. The apexes of the inner rotor are in contact with the epitrochoid at all times, which simplifies their sealing. The rotors are rotated in the same direction about their respective axis at a speed ratio of the outer rotor to the inner rotor of $n - 1/n$, where n is equal to the number of lobes of the epitrochoid. The speed ratio particularly suitable for an efficient and still simple cycle is $3/2$.

In one configuration, both rotors rotate at this speed ratio, while in the other configuration the outer rotor is stationary and the inner rotor has a planetary motion about the axis of the outer rotor. The relative motion of the two rotors, however, is the same in both the cases. The configuration in which both the rotors rotate is referred to as the dual rotation type and the engine based on this is called Drehkolbenmaschine, or D.K.M. type. This engine was first designed by Wankel and his associate Ernst Hoeppner. From the standpoint of sealing operation and balancing this engine was proved to be advantageous. But this resulted in not only a costly but also a complicated design presenting its own peculiar problems. For instance,

the incoming charge passed through the output shaft; moreover, a sparking plug had to be fitted to each rotor flank, and this necessitated slip-ring connections and made cleaning or servicing of the plugs a major operation. It is, of course, possible that the induction through the output shaft might have solved the cooling problem of the rotor, but on balance this engine must be considered a complex piece of machinery. In view of this conclusion, the D.K.M. engine experienced a setback.

The engine based on the other configuration and titled Kreiskolbenmaschine, or K.K.M. type, was designed by Wankel and Walter G. Froede, built and tested by N.S.U. Notorenwerye A.G., Germany. K.K.M. is a kinematic inversion of the D.K.M. design. In this engine only the rotor and eccentric output shaft rotate at the appropriate different speeds; the induction and exhaust passages are in the stationary cylinder or its end covers. A spark plug is fitted to the cylinder, where it is accessible, and no slip-rings are required for the ignition.

In the D.K.M. engine both the rotor and casing were rotating in the same direction. The speed ratio of these two parts was 2:3, resulting in a velocity of the rotor relative to the casing of 1/3. The same relative velocity between the rotor and casing is maintained in the new engine with a planetary motion of the rotor. In order to satisfy these conditions an ingenious design has been adopted. While the rotor revolves bodily about the mathematical fixed point, in this case the center of symmetry of the casing, it also rotates about its own axis (eccentric to that of the main axis), but in opposite direction

and with an angular velocity of 2/3 of the main axis. A positive angular displacement of 90 degrees of the latter corresponds to a 60-degree negative angular displacement of the rotor relative to its own axis. The positive angular velocity of the rotor relative to the main axis, therefore, is only 30 degrees. This means that three revolutions of the main shaft correspond to one revolution of the rotor. The correct ratio of the two angular velocities is effected by a reduction gearing, comprising an internally geared annulus attached to the rotor and a fixed externally geared reaction member located at one side cover of the casing, coaxially with the main shaft. By and large, this engine is proved to be better than the other. Hence N.S.U., of Germany, and the Curtiss-Wright Corporation, of the U.S.A., are working on the design and development of this engine.

Optimum Shape

Epitrochoid is one of the numerous varieties of epicyclic curves and represents the path traced by a point on the radius of a circle, rolling without sliding on the outer circumference of another fixed circle. The hypotrochoid is generated in a similar way by a point on the radius of a circle rolling on the inner circumference of a fixed circle. If an epitrochoid or a hypotrochoid is rotating about an axis, and another appropriate body, representing either the inner or the outer envelope of the trochoid, rotates on another parallel axis in the same direction but with a different angular velocity, then spaces are formed

between the trochoid and the envelope, the area of which varies between a minimum and a maximum according to a sine function.

Figure 1 reveals two positions of the rotor which give the maximum of a working chamber at the bottom dead center and the minimum volume at the top dead center. The difference between these volumes constitutes the displacement of the engine and their ratio the theoretical compression ratio. A cut-out in the inner rotor provides the actual desired compression ratio and a gas transfer passage at the top dead center.

The shape of the epitrochoid is determined by the ratio of the eccentricity e to the length of the generating radius R. Figure 1 shows how, for the given volume V_c of one chamber, the size and the shape of the trochoid casing can vary considerably. For the ratio $R/e = \infty$ it is obviously a circle, for a ratio of 11.5:1 it resembles an ellipse, while for smaller ratios the curve has two indents in its small axis which are rather small at the ratio $R/e = 7.1$ but very pronounced at the ratio $R/e = 3.9$. The R/e ratio also determines the maximum angle of obliquity α, which the generating radius forms with the normal to the curvature. It is necessary to keep this angle fairly small to facilitate the scaling between the apex of the rotor and the path of the casing. The maximum deviation of α from the normal should not exceed $\pm$ 30 degrees, which corresponds to an R/e ratio of something between 6 and 7. The figure also shows the influence of the R/e ratio on the variation of the area of each individual cell during the rotation of the rotor, and thus on the theoretical compression ratio ε.
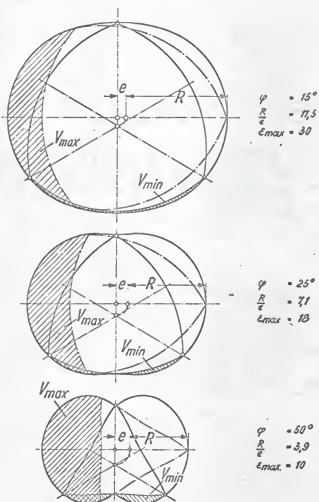
Fig. 1. Two-lobe epitrochoid with inner envelope
effect of trochoid-shape on overall dimension
of engines comprising identical
swept volume.

It is interesting to note that Felix Wankel's epitrochoid
was obtained empirically. Professor Othmar Baier, of the Tech-
nical College, Stuttgart, proved the shape to be an epitrochoid
and thus facilitated the mathematical analysis and investiga-
tions, which proved of the utmost value in evolving a rational
method for machining the bore.

Principle of Operation

The principle of operation of the K.K.M. type of N.S.U.-
Wankel engine is explained with reference to Fig. 2, which
represents a diagrammatic section during a complete revolution
of the output shaft. Since the piston, while being rotated for-
ward, counter rotates at two-thirds of the shaft speed, its
actual speed relative to the casing is only one-third that of
the shaft, a fact which is significant as it implies a compara-
tively low sliding speed even at a high rate of revolution of
the output shaft. It also means that there is one working
'stroke' during each revolution of the shaft.

As is seen from the diagram, the piston or rotor intercepts
three spaces between its faces and the epitrochoidal inner sur-
face of the casing. As the piston rotates, these spaces grow
and diminish rather like the volume inside the cylinder of a
reciprocating engine as the piston moves up and down, but with
a mutual phase difference of 120 degrees. While one working
space is in the suction phase the next is undergoing compression
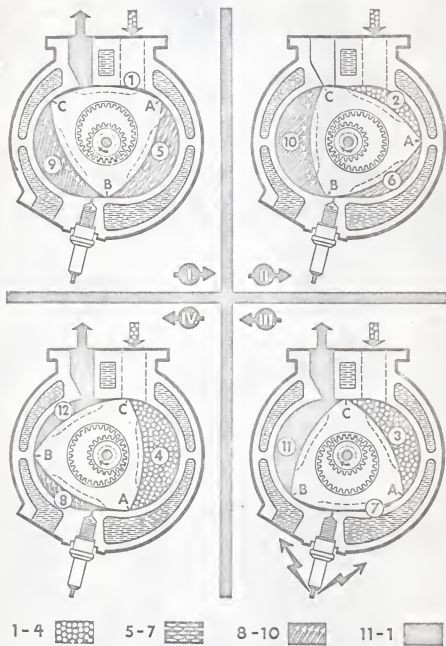and ignition, while the third goes through the stages of

Fig. 2. Four-cycle operation of the Wankel
engine; intake (1-4), compression (5-7),
expansion (8-10), exhaust (11-1).

expansion and exhaust. The cycle is therefore a true four-
stroke cycle.

No valves or valve gear are required since the rotating
piston itself covers and uncovers the inlet and exhaust ports
in turn. By the positive division of the working spaces due to
the adoption of four-stroke operation, even running at all loads
and low specific consumption are obtained. The adequate cooling
and absence of hot spots make the engine insensitive to a low
octane number. A balancing mass and flywheel are provided to
compensate the inertia forces arising from the planetary motion
of the piston and to provide more even running. Water cooling
is used although it is thought that air cooling may be possible
later. It would appear that the only suitable method of lubri-
cation is by a petrol and oil mixture, as with two strokes.

Engine Cycle

This engine works on otto cycle. Figure 3 shows how the
engine would run on an ideal cycle on P-V coordinates. For the
reciprocating engine the equivalent cylinder volume and the
corresponding piston position below the volume axis could be
indicated. But for the rotary engine this may not be done and
it may be correlated by position numbers.

The numbers of the cycle of Fig. 3 correspond to the num-
bered volumes and positions shown in Fig. 2. Fuel-air induction
takes place through 1-2-3-4, next compression of the fuel-air
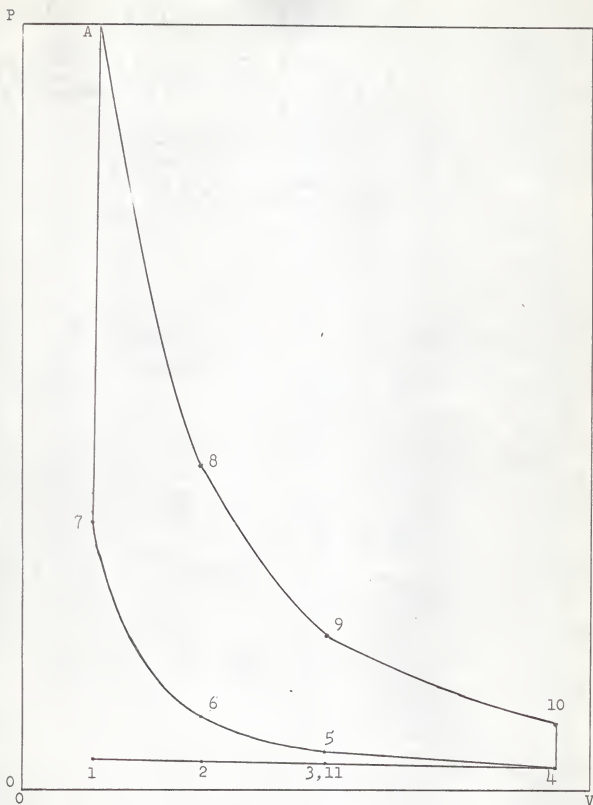charge through 4-5-6-7. Ignition of the mixture takes place at

Fig. 3. Ideal P-V diagram. Numbers correspond to
rotor position in Fig. 2.

7 for a sharp pressure rise to A. Then expansion and work take place through A-8-9-10. Most of the gas blows out of the cylinder as the exhaust port is uncovered after position 10. Then the rotor squeezes the rest of the spent gas from the compartment through 10-11-12-1. Actual engine cycle will differ from this ideal because of irreversibilities and heat transfer.

First Prototype

The first prototype of 125-cc chamber volume was tried on the test bed on February 1, 1957, and long firing sequences were immediately obtained (1). In this early engine both casing and piston were rotating. The specific consumption of this early engine was of the order of 250 grams per brake horsepower per hour. Mean effective pressures up to 8.5 kilograms per square meter were obtained, giving outputs of 29 bhp at 17,000 rpm of the casing (11,300 rpm of the rotor), with satisfactory power even at speeds as low as one-tenth of this. The 125-cc prototype weighs only 17 kg in cast iron and steel, and 11 kg in light alloy.

The whole design thus assumes an extreme degree of simplicity and compactness.

COMPARISON WITH RECIPROCATING ENGINE

Combustion

An important difference between the Wankel rotary engine and the reciprocating engine is obviously the shape of the combustion chamber in all phases from top dead center to the bottom dead center. For the process of combustion, it is important that in the rotating combustion engine the volume, which includes the burning gas, is traveling while the combustion process takes place. All the thermodynamic phases occur in successive angular positions in the rotary engine, whereas in the reciprocating engine the phases occur in one place and are separated by time only.

Port Area

The Wankel engine resembles a two-stroke engine in respect to the control of the gas exchange. Inlet and exhaust ports, arranged in the circumference of the casing, are covered or uncovered, respectively, by the three radial seating elements of the rotor. It is obvious that ports of adequate dimensions offer larger and less restricted flow areas than valves so that in the absence of the turbulence caused by valve plates and valve stems, the effective gas exchange area is decidedly favorable. Further, the steep rise and the rapid closure of the ports permit a shortening of the timing angle. These conditions

are shown in Fig. 4, presenting a comparison between the port
opening area of a K.K.M. engine of 125-cc chamber capacity, and
the valve lift diagram of a 125-cc, air-cooled N.S.U. motorcycle
engine, both running at 12,000 rpm. In order to obtain compar-
able data for the gas exchange, the speed of the K.K.M. engine
has been based on the 'thermodynamic speed', which is two-thirds
of the shaft speed, to allow for the difference between the 270
degrees 'stroke' of the rotary engine compared to the 180 degrees
stroke of the orthodox engine. The steep rise of the port open-
ing curve permits the utilization of the pressure at the end of
the expansion period to the fullest extent, while the rapid
closure offers the possibility of making use of the 'dynamic
supercharging' effect.

P-V Diagram

A comparison between the P-V diagrams of a K.K.M. 125-cc
engine and that of the 125-cc conventional piston engine (Fig. 5)
shows that the difference between these two engines in respect
to the compression, the rate of pressure rise, and the expansion
is very small. Such a positive result is actually surprising
because one would expect the combustion process of the Wankel
engine to be negatively affected by the increased rate of heat
transfer of the gas flowing along the large cooled areas of the
casing at considerable velocity. The fact that excessive heat
losses and leakage losses are not discernible in the P-V diagram
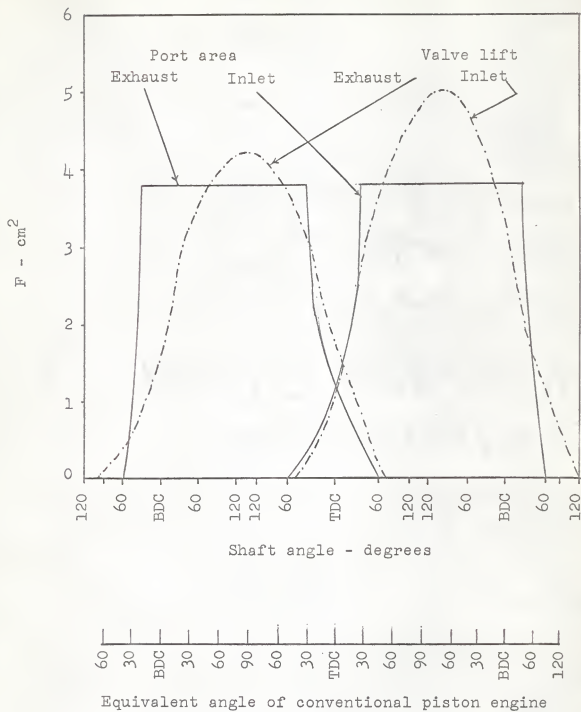gives reason to believe that the Wankel engine in thermodynamic

Fig. 4. Port area of Wankel engine of 125-cc chamber
volume compared to valve lift diagram of
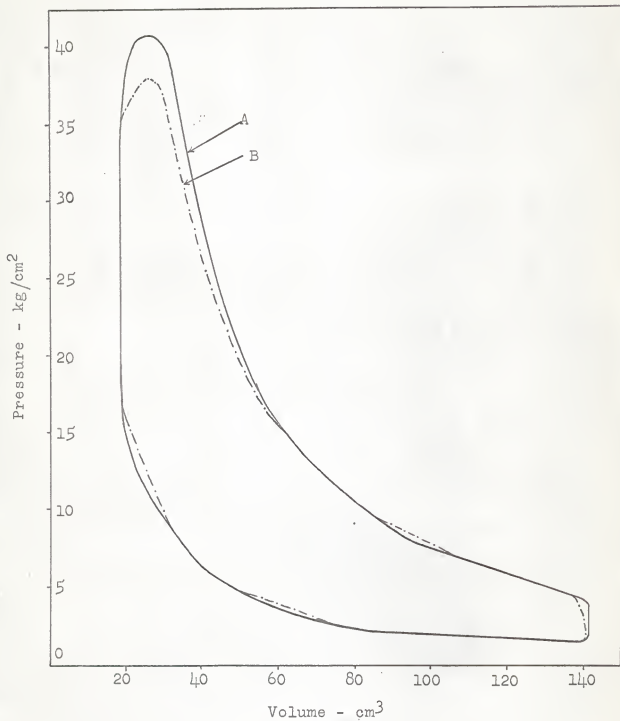125-cc conventional engine.

Fig. 5.   Pressure-volume diagrams of 125-cc four-
stroke piston engine (A) and of
type KKM 125 (B).

respect is just as efficient as the conventional engine.

Sealing System

Different from the piston ring arrangement in a reciprocating engine, the rotary combustion engine has only one sealing line of contact. It may appear that it can never reach the same tightness as a piston inside a round cylinder bore. But it is to be considered that each piston ring requires a gap which is necessary because of different temperature expansion of piston and cylinder. The sealing of the rotary engine has no gap except the required clearance within the fit of all components. The major difference between the two systems is that a worn piston ring inside a worn cylinder has an enlarged gap, whereas regardless of wear the continuous sealing line of contact along the periphery of the rotor stays tight.

The elements of the sealing system, which are shown in the exploded layout in Fig. 6, comprise a radially movable apex seal blade which is located in a radial groove in the center plane through the apex. Close to both side walls, the radial inner portion is guided in axially movable interconnecting bolts. The side sealing strips extending from apex to apex are in overlapping engagement with these bolts. All parts are preloaded toward the surrounding walls of the housing by wave springs. The main sealing force is produced by the gas pressure itself, and therefore is variable during the relative movement of the rotor. The end face sealing elements are in contact with the side wall
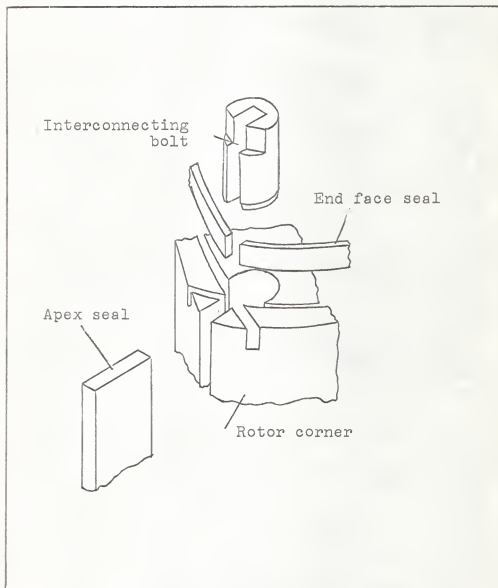
Fig. 6. Components of seal arrangement.

of the housing on a plane surface area, whereas the apex seals possess only a sealing line of contact.

Cooling

Liquid cooling has been used for both the housing and the rotor. The former is water-cooled and the latter is cooled by lubricating oil pumped through the main shaft. The rotary engine, unlike the reciprocating engine, always exposes the same stationary housing locations to the same portion of the cycle. The housing cooling has been designed as a multipass forced-flow system. The cooling liquid flows back and forth through the rotor housing and between the end housing walls. The rotor housing flow passages are parallel to the engine axis; the internal ribbing of the end housings redirects the flow.

Thus we observe that there are more differences than similarities between the reciprocating and rotary engines.

DESIGN OF N.S.U.-WANKEL ENGINE

The main factors that influence the design of the N.S.U.-Wankel engine are:

1. That it should incorporate all the components ultimately necessary to give an engine which would have a fuel consumption competitive with the reciprocating engine.
2. That it could, with manufacturing development, be produced at an economical price.

3. That it would be safe and reliable.

The design of an engine may be regarded as a series of choices providing increasing amounts of information regarding the final design as the series proceeds.

Under ideal conditions each type of prime mover has a field of application in which it has advantages over all others. Frequently, however, the conditions of a particular application promptly eliminate certain types of prime movers, leaving the remaining types to be studied and compared in detail. It has often been predicted that the N.S.U.-Wankel engine will completely replace the reciprocating piston engine within a given period. Predictions of this nature seldom mature since each type of engine finds its own particular field of application.

The N.S.U.-Wankel engine is essentially a high-speed engine. It may be particularly suitable for sports cars. The first car to use this engine is the N.S.U.-Spider, a two-seater sports car. Trucks, buses, and other heavy machinery require high initial torque characteristics. As this engine cannot develop so high an initial torque, it may not be a rival to the conventional engine in this field. A commendably flat consumption curve of this engine is a favorable point for application to the passenger cars. But the problem of sealing will be severe if rotor diameter gets larger. Under these situations, it seems to be a strong contender for the small European-size cars.

Output

The N.S.U.-Wankel may be regarded, with respect to the chamber capacity, as a two-stroke engine, though the cycle itself is clearly that of a four-stroke engine. It follows that for the purpose of determining the output of the engine in terms of the speed of the drive shaft, the orthodox formula relating to two-stroke engines may be used.

If V_c represents the swept volume of one chamber in cubic feet, N the rotational speed of the output shaft in rpm, and p_{me} the mean effective pressure in pounds per square feet, then the effective output P in horsepower amounts to

$$P = \frac{3\ p_{me}\ V_c}{550 \times 60} \cdot \frac{N}{3}$$

which is equivalent to that of a three-cylinder, two-stroke engine of a capacity of V_c cubic feet, transmitting its torque to the drive shaft at a step-up ratio of 3:1.

When simplifying the above formula to

$$P = \frac{p_{me}\ V_c\ N}{33,000}$$

it is apparent that the output and consequently the cyclic irregularities of a Wankel engine of V_c chamber capacity, are comparable to those of a single-cylinder two-stroke engine of V_c cylinder capacity.

In comparison with the latter engine, however, the brake mean effective pressure of the Wankel engine, employing the four-stroke cycle, is at least 50 per cent higher. The high

brake mean effective pressure and the high output speed together account for the small bulk and weight of the Wankel engine. On the other hand, they indicate that the engine is subject to considerable thermal loading.

Swept Volume

The volume change with rotation of the piston is sinusoidal. The total volume of the casing has been calculated by Gerard Kelles (16) to be

$$V = h\left[\pi e^2 + \frac{\pi}{3} R^2 - \frac{\sqrt{3}}{4} R^2 - \frac{3\ eR\sqrt{3}}{2} \cos\left(\frac{2\ \beta}{3} + 120^0\right)\right]$$

where h = thickness of the engine

e = eccentricity

R = generating radius

and β = the angle described by the line passing through the point of contact of the meshing gears and the center of the circular hole in the rotor with reference to a fixed axis.

Maximum volume is given when the value of

$$B = \frac{\pi}{2}\ ,\ \frac{7\ \pi}{2}\ ,\ \frac{13\ \pi}{2}\ ,\ \ .\ \ .\ \ .\ \ .$$

Minimum volume is given when the value of

$$\beta = 2\pi,\ 5\pi,\ 8\pi,\ .\ \ .\ \ .\ \ .$$

$$V_{max} - V_{min} = 3\sqrt{3}\ \ eRh$$

Swept volume $V_{swept} = 3\ \sqrt{3}\ eRh$

For the optimum shape of the trochoid,

$$\frac{R}{e} \cong 7$$

For an efficient cooling of the engine,

$$\frac{h}{e} \cong 4$$

$$V_{swept} = 3 \sqrt{3} \cdot e \cdot 7e \cdot 4e$$

$$= 84 \sqrt{3} \ e^3 \qquad (1)$$

If the maximum volume is known, minimum volume can be calculated by

$$V_{min} = \frac{V_{max}}{\mathcal{E}}$$

where $\mathcal{E}$ = compression ratio.

The compression ratio of the engine is found to be 8.5:1.

$$V_{min} = \frac{V_{max}}{8.5}$$

$$V_{swept} = V_{max} - V_{min} = V_{max} - \frac{V_{max}}{8.5}$$

$$= (1 - \frac{1}{8.5}) \ V_{max} = \frac{75}{85} \ V_{max} \qquad (2)$$

Equating (1) and (2),

$$\frac{75}{85} \ V_{max} = 84 \sqrt{3} \ e^3$$

$$e^3 = \frac{75}{84 \times 85 \sqrt{3}} \ V_{max} \doteq 0.00606 \ V_{max}$$

$$e = \sqrt[3]{0.00606 \ V_{max}}$$

Then   R = 7 e

            h = 4 e

            r_R = 3 e

            r_S = 2 e

Engine Geometry

A mathematical analysis of the engine geometry has been made by W. A. Woods, of the University of Liverpool [20].

The rotor and the notation are shown in Fig. 7, in which the dimensions, particularly the eccentricity e, have been exaggerated for convenience. The rotor ABC is shown as an equilateral triangle; the point G is the centroid, and GA is the generating radius. In the general position, the line OG is inclined at an angle θ to the x-axis.

The locus of A is therefore

$$x = e \cos \theta + R \cos \frac{\theta}{3}$$

$$y = e \sin \theta + R \sin \frac{\theta}{3}$$

This is the equation of a particular epicyclic and a special form of an epitrochoid.

The point of interest occurs when $\theta = \frac{3\pi}{2}$; here x = 0. Hence examining the equations for turning points by differentiation and equating to zero, there is a turning point at $\theta = \frac{3\pi}{2}$ provided that $\frac{R}{e} \neq 3$.
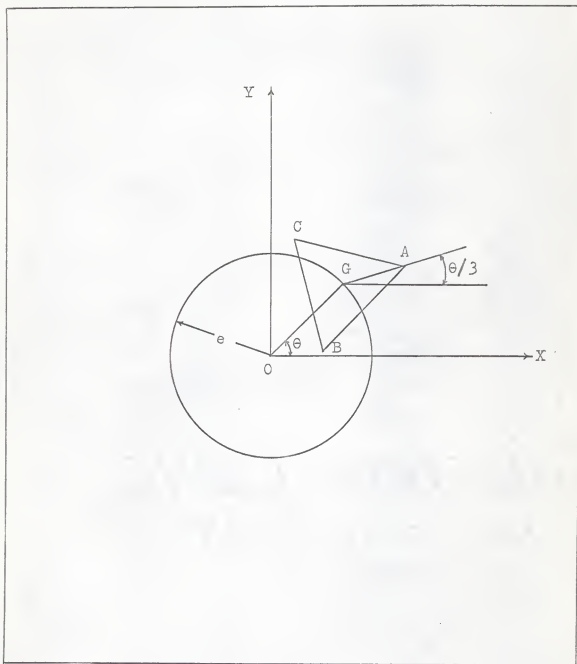
Fig. 7. Exaggerated geometry.

Proceeding to determine the nature of the turning point by a second differentiation, this shows that the turning point is a minimum provided $\dfrac{R}{e} < 9$ and a maximum if $\dfrac{R}{e} > 9$.

A family of curves has been constructed which is shown in Fig. 1. It is seen that in the case $\dfrac{R}{e} = 3.9$ a cusp is present at $\theta = \dfrac{3\pi}{2}$ and in other cases the appropriate maxima and minima are shown.

In the practical case the pitch circle of the rotor gear has a radius r_R and the output shaft gear a radius r_S.

From Fig. 2, $\qquad \dfrac{r_R}{r_S} = \dfrac{3}{2}$

From Fig. 7, $\qquad r_R - r_S = e$

Therefore $\qquad r_R = 3\,e \quad$ and $\quad r_S = 2\,e$

The maximum size of the rotor gear will be close to the case where the rotor gear pitch becomes the inscribed circle of the triangle ABC. In this case, $r_R = \dfrac{R}{2}$, and therefore $\dfrac{R}{e} = 6$. Hence $\dfrac{R}{e}$ for a practical engine will probably lie in the range $6 < \dfrac{R}{e} < 9$. The ratio adopted in the engine is about 7.

CONCLUSIONS

As the conventional reciprocating combustion engine has serious limitations in regard to thermal efficiency, various alternative power plants are being studied. As an alternative, rotary combustion engines seem to be promising. A number of rotary engines have been proposed by quite a few designers. A review of these designs reveals the fact that there is a variety of the possible arrangements of the rotor engine.

Of the many engines, the N.S.U.-Wankel engine appears to be a major breakthrough in internal combustion engine design. This high-speed engine has an appreciable power-to-weight ratio. Compactness, smoothness of running, and reliability of operation are other points on the credit side. This engine may launch a new era in high thermal efficiency.

This engine shows promise for limited applications and may replace the conventional engine in certain fields.

ACKNOWLEDGMENT

The author is highly indebted to Professor A. H. Duncan, Professor of Mechanical Engineering, Kansas State University, for his valuable guidance and encouragement during the preparation of this report.

REFERENCES

1. Anonymous.
   Rotary four-stroke engine. The Engineer, Dec. 18, 1959,
   p. 834.

2. Anonymous.
   Rotary piston engine symposium. The Engineer
   Feb. 26, 1960, pp. 365-370.

3. Anonymous.
   Some epitrochoidal engine developments. The Engineer,
   Nov. 22, 1963, pp. 846-847.

4. Anonymous.
   Selwood orbital engine. Automobile Engineer,
   June, 1961, pp. 218-220.

5. Ansdale, R. F.
   N.S.U.-Wankel engine. Automobile Engineer, May, 1960,
   pp. 166-176.

6. Ansdale, R. F.
   Rotary combustion engines, Part I. Automobile Engineer,
   Dec., 1963, pp. 518-524.

7. Ansdale, R. F.
   Rotary combustion engines, Part II. Automobile Engineer,
   Jan., 1964, pp. 20-27.

8. Ansdale, R. F.
   Rotary combustion engines, Part III. Automobile Engi-
   neer, Feb., 1964, pp. 52-56.

9. Bentele, M.
   Curtiss-Wright's developments on rotating combustion
   engines. S.A.E. Trans., Vol. 69, 1961, pp. 194-200.

10. Bentele, M.
    New rotating combustion engines by Curtiss-Wright.
    S.A.E. Journal, May, 1961, pp. 33-36.

11. David, Scott.
    Rotary cylinder engine has non-reciprocating pistons.
    Automotive Industries, Aug. 1, 1961, pp. 50-51.

12. Froede, W. G.
    The N.S.U.-Wankel rotating combustion engine. S.A.E.
    Transactions, Vol. 69, 1961, pp. 179-193.

13. Froede, W. G.
    Seals among N.S.U. developments on rotating combustion
    engines. S.A.E. Journal, April, 1960, pp. 50-56.

14. Hurley, R. T.
    The rotating combustion engine. S.A.E. Transactions,
    Vol. 69, 1961, pp. 641-649.

15. Hurley, R. T.
    CW rotating combustion engine delivers 2 hp per cu in.
    S.A.E. Journal, June, 1960, pp. 80-85.

16. Kelles, Gerard.
    Theoretical studies over the N.S.U.-Wankel motor.
    Thesis submitted at the University of Leuven, 1962.

17. Starkman, E. S.
    What engine will power the car of tomorrow?
    S.A.E. Journal, April, 1964, pp. 34-39.

18. Walter, Clark Dean.
    A new rotary piston engine. Mechanical Engineering,
    Oct., 1964, pp. 44-46.

19. Witzky, J. E.
    Internal combustion engines--a forecast. Mechanical
    Engineering, Nov., 1964, pp. 36-42.

20. Woods, W. A.
    N.S.U.-Wankel engine. Engineering, Jan. 15- 1960,
    p. 76.

A SURVEY OF ROTARY TYPE INTERNAL COMBUSTION
ENGINES WITH PARTICULAR EMPHASIS
ON THE N.S.U.-WANKEL ENGINE

by

HIRIYUR VEERANNA CHANDRASHEKAR

B. S., Mysore University, India, 1958

————————————

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

The conventional reciprocating internal combustion engine suffers from several fundamental shortcomings. A major loss of power occurs during the conversion of linear reciprocating motion into rotary movement. Undesirable vibrations are caused due to the nonuniform torque. There is a basic mechanical and thermal limitation imposed on the power-plant ratio. The piston rings will seize and the valves will burn on stepping up the thermal loading. At high rates of revolution under inertia forces, valve gears and other reciprocating parts may fail to operate. The operational speed is limited by the stresses developed due to the reciprocating motion. Despite these defects this engine has been reigning in the automotive field for eighty-odd years.

The idea of doing away with reciprocating motion is not new. The first applications of the rotary principle can be traced back to James Watt and his co-worker Murdock. Other famous engineers like James Ericson, Westinghouse, de Laval, and Parsons worked on rotary engines. None of their designs, however, were successful, largely because the sealing problem could not be solved with the scant knowledge and means available at that time.

Of late the supremacy of the time-proved engine has been seriously challenged by a number of positive displacement rotary engines. Various solutions have been suggested to the problem of sealing. Quite a few of the engines are of academic interest only; many practical considerations are overlooked. Several designs are just experimental curiosities, but it was from an

experimental curiosity that the reciprocating engine had its beginning. Some of the engines have been built and tested; the results are encouraging and are worthy of serious consideration.

In view of the merits and disadvantages of the proposed engines, the N.S.U.-Wankel engine seems to be more promising than others. This has all the appearances of being a revolutionary design and there is an impressive list of favorable points to its credit. The inventor has taken from the reciprocating piston engine only the system of introduction of fuel and the ignition system based on the four-cycle principle. This is also comparable to a turbine, since it possesses no parts which operate in reciprocal motion. Thus the N.S.U.-Wankel engine may be labeled a hybrid engine which is a result of a cross between an orthodox reciprocating engine and a modern reaction turbine.

Curtiss-Wright Corporation, Wright Aeronautical Division, Wood-Ridge, New Jersey, and N.S.U., Notorenwerye, A.G., Germany, are working on the design and development of this engine.

In this report the designs proposed by a host of inventors have been analyzed to point out certain advantages and disadvantages. Also, a particular design of the N.S.U.-Wankel engine is developed in order to show the design procedure and associated problems.