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Starting Low Compression Ratio Rotary Wankel Diesel Engine

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ABSTRACT

The single stage rotary Wankel engine is difficult to convert into a diesel version having an adequate compression ratio and a compatible combustion chamber configuration. Past efforts in designing a rotary-type Wankel diesel engine resorted to a two-stage design. Complexity, size, weight, cost and performance penalties were some of the drawbacks of the two-stage Wankel-type diesel designs. This paper presents an approach to a single stage low compression ratio Wankel-type rotary engine. Cold starting of a low compression ratio single stage diesel Wankel becomes the key problem. It was demonstrated that the low compression single stage diesel Wankel type rotary engine can satisfactorily be cold started with a properly designed combustion chamber in the rotor and a variable heat input combustion aid. A 10.5 compression ratio rotary Wankel-type engine was started in 15 secs at -10°C inlet air temperature. High cranking speeds and white smoke were the biggest drawbacks of this design.

THE SIMPLE ROTARY WANKEL ENGINE offers high power density, high speed, and smooth vibration-free operation. These attributes were highly sought after in a diesel engine. A diesel rotary-type Wankel engine was hoped to overcome many of the undesirable features of the reciprocating diesel engine.

Rolls Royce of England (1)* and Yanmar Diesel Engine Co. (2) of Japan embarked on a two-stage diesel Wankel engine development program in the late sixties. The solutions found to overcome the Wankel-type rotary engine for diesel operation were major and as detrimental as the drawbacks of a reciprocating diesel engine.

The single stage diesel Wankel, if it can be developed, is still considered the attractive way to take advantage of the rotary Wankel engine concept. Yanmar Diesel Engine Co. and Cummins Engine Co. entered into a joint development program to determine the feasibility of the single stage diesel Wankel-type rotary engine in 1972. The results of this investigation are presented as a basis of continued work in this area in view of revewed interest in the Wankel engine. New technologies such as the adiabatic engine, turbocompounding, adaptation of the Miller cycle, stoichiometirc diesel, etc. can all aid in improving the outcome of a modern, high speed, compact, high power density, multi-fuel capability, diesel Wankel-type rotary engine.

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* Numbers in parentheses designate references at end of paper

TEST EQUIPMENT

A photograph of the test set-up used in this investigation on starting a low compression ratio single stage diesel Wankel engine is shown in Figure 1. The sparkignited Yanmar R450 (450cc displacement) 8.0:1 compression ratio Wankel engine was converted to diesel fuel injection for this investigation.

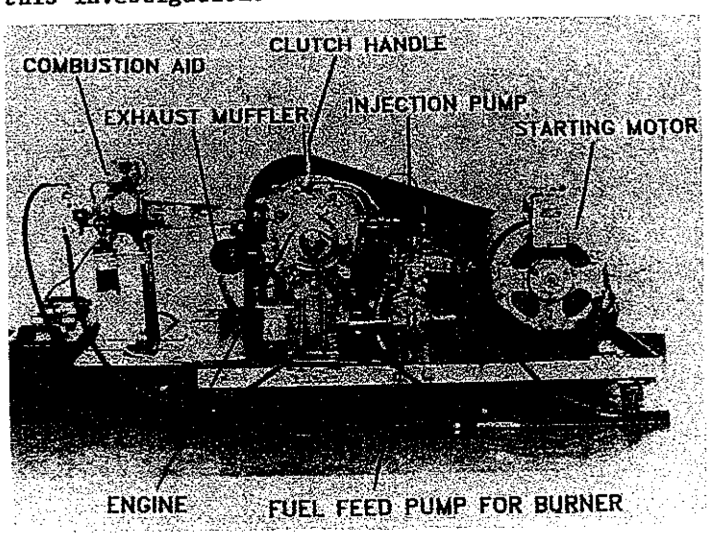


Figure 1. Photo of test equipment.

The variable heat input to the intake port of the Wankel engine was supplied by the combustion aid. The combustion aid was supplied with a variable fuel rate from the feed pump. The fuel to the combustion aid was ignited by a battery source, exciter, and spark plug shown in Figure 1. The electric motor supplied adequate starting power to the Wankel engine through a jaw clutch. The Bosch-type injection pump is located near the feed pump for the combustion aid.

A variable speed electric motor was used to start the Wankel diesel engine through a belt drive and a jaw clutch. Upon starting the Wankel engine, and as soon as selfsustained operation was effected, the clutch was disengaged.

The diesel nozzle of the combustion aid (3) was supplied with the same fuel as the diesel Wankel engine. The fuel nozzle was an air atomizing type and ignited by a long-reach spark plug.

TEST PROCEDURE

Five different types of Wankel engine rotors were tested. These different types of rotors are shown in Figure 2. The compression ratios of the rotor for types A, B, C and E were essentially 10.7:1. Type D's compression ratio was 8.5:1.

The injector opening pressure was kept at 290kg/cm^2 and the number of holes was 6 x 0.25mm. The quantity of injected fuel was 96.5mm^3/stroke.

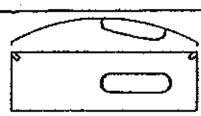
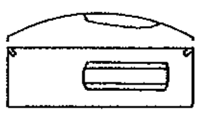
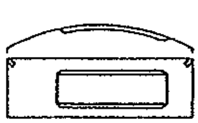
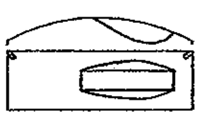
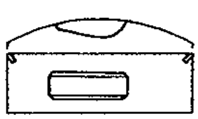
TYPE	CONFIGURATION & LOCATION OF RECESS	INJECTOR LOCATION	C.R.	INJECTION TIMING. °BTDC	START	NO LOAD RUNNING, RPM 1000 2000 3000
A		L	10.5	115	OK	
B		L	10.2	95	OK	
C		L	10.6	75	OK	
D		L	8.5	115	NO	
E		L	10.7	75	OK	
		T	10.7	35	OK	

Figure 2. Five types of rotors tested for cold start of diesel Wankel engine.

The procedure for starting was as follows:

1. Clutch engaged between starting motor and Wankel diesel engine to achieve constant cranking speed.
2. Combustion aid burner ignition turned "on."
3. Time to start determined when 110% Engine overspeed under self-sustained operation is reached.
4. Clutch disengaged and Wankel diesel permitted to rev up.

Figure 3 shows a diagram of the starting procedure. The variables are the engine speed (in rpm) and time (in seconds). The cylinder pressures are plotted graphically. During acceleration (rev up), the cylinder pressure is approximately 30kg/cm^2 and at constant speed the cylinder pressure drops to 20kg.cm^2. Typical cylinder pressure diagrams at 1000, 2000, and 3000 rpm are shown in Figure 4. Note the consistent firing diagram at no load conditions.

TEST PARAMETERS

Four basic tests were designed to provide the necessary information for the cold start of a low compression ratio single stage diesel Wankel engine. They were as follows:

I. Screening of combustion chamber
II. Selection of cranking speed
III. Cold start tests
IV. Sustained operation.

Five types of rotor combustion chambers were fabricated and tested. They are identified as Types A, B, C, D and E and are shown in Figure 2. The compression ratio for each type of rotor is identified in Figure 2. The relationship between the location of rotor recess and injector is shown in Figure 5 for the cases of Trailing and Leading injector locations.

The important parameters considered and sought in the test program were:

Main injection charge	cc/min
Ambient temperature	°C
Inlet charge temperature	°C
Cranking speed	rpm
Injection timing	°BTDC
Rotor type	A, B, C, D, E
Injector location	Trailing or Leading
Combustion aid fuel flow	cc/min
Sustained engine speed	rpm
Time to start	secs
Oxygen in inlet charge	percent
Exhaust temperature	°C
White smoke	subjective
Compression ratio	-
Quantity of charge	cc/min
Pressure diagram	kg/cm^2
Injector opening pressure	kg/cm^2
N x diameter holes	no. x mm

TEST CONDITIONS:	
Cranking Speed	800 rpm
Rotor	Type E
Injection Time	35° BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Quantity of Injected Fuel	96.5mm^3/stroke
Fuel Flow to Burner	5.0cc/min.

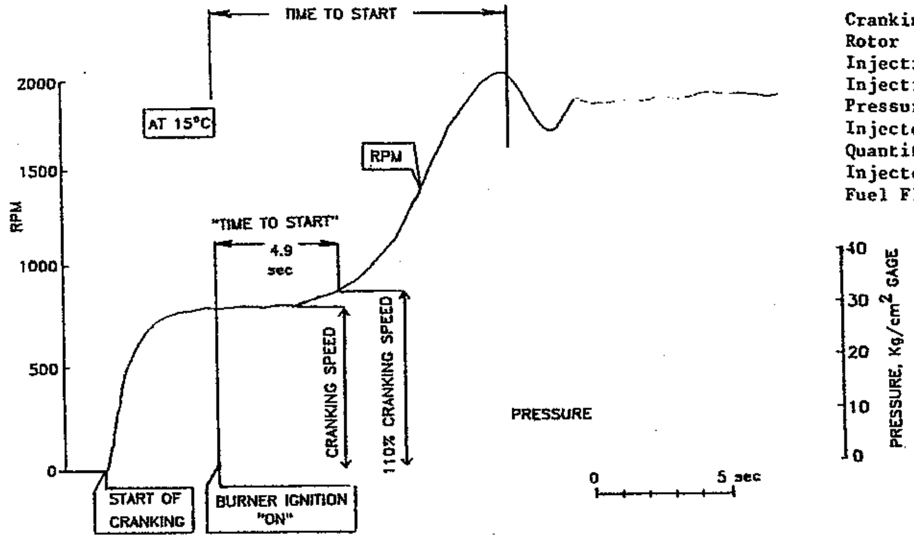
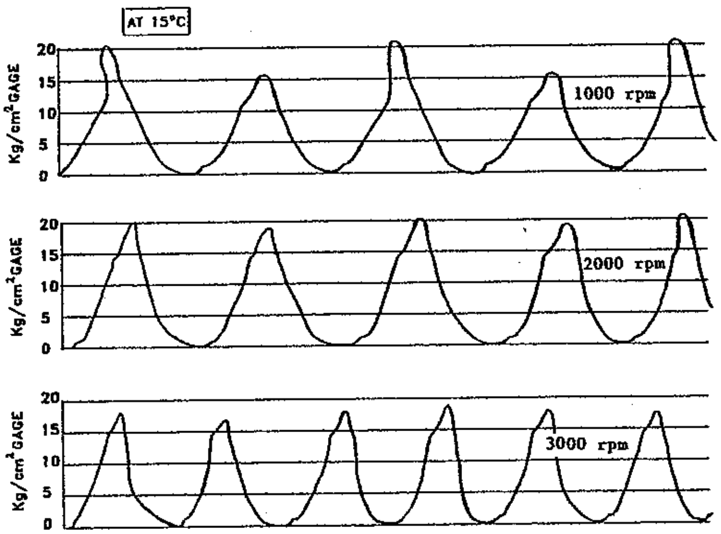


Figure 3. Diagrams of shaft speed and gas pressure in start (at 15°C).



NOTE:	
Rotor	Type E
Injection Time	35°BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Temperature of Charge	120~140°C

Figure 4. Pressure diagram in no load running.

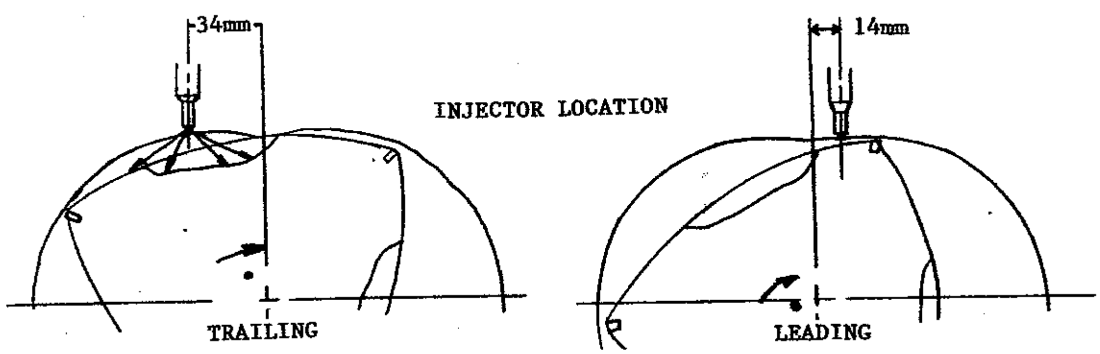


Figure 5. Relationship between location of rotor recess and injector.

The test parameters delineated above have been combined in a test matrix for test objectives I, II, III, and IV as shown in Figure 6. The identified parameters are the test variables, and the circled question marks are the parameters sought in tests I, II, III and IV. Additional test variables that were kept constant were:

Injection pressure	290kg/cm^2
Injector hole x diameter	6 x 0.25 mm

TIME TO START - Figure 7 shows the resultant time to start with the type E rotor at 10.7:1 compression ratio and at 15°C and -10°C ambient temperature. At 800 rpm cranking speed, it is seen that there is an optimized air-fuel ratio for the combustion aid for minimum starting time. The optimized air-fuel ratio is about 55:1. An air-fuel ratio lean than 85:1 results in charge air temperatures too low for the ignition of diesel spray. An air-fuel ratio richer than 35:1 results in the depletion of

	INJECTION QUANTITY, mm^3/stroke	AMBIENT TEMPERATURE, °C	CHARGE OF TEMPERATURE, °C	CRANKING SPEED, rpm	INJECTION TIMING, °CA BTDC	ROTOR TYPE	INJECTOR LOCATION Trailing/Leading from TDC	COMBUSTION AID FUEL FLOW cc/min.	SUSTAINED SPEED, rpm	TIME TO START	OXYGEN IN CHARGE	QUANTITY OF CHARGE
(I) SCREENING OF COMBUSTION CHAMBER ROTOR	---	+20	---	800	(?)	A B C D E	TRAILING	---	(?)	(?)	---	---
(II) SELECTION OF CRANKING SPEED	---	+20 -5 -10	(?)	(?)	35	E	TRAILING	---	---	(?)	---	---
(III) COLD START TEST	96.5	+15 -10	(?)	800	35	E	TRAILING	(?)	---	(?)	(?)	(?)
(IV) SUSTAINED OPERATION	---	+15 -10	(?)	---	35 55* 35* 5* 10*(ATDC)	E	TRAILING	(?)	1000 1500 2000 2500 3000	---	(?)	(?)

* White smoke observation

Figure 6. Matrix of cold start test variables against test objectives I, II, III and IV. Circled question marks are parameters sought in tests.

Upon starting the engine, other variables sought for test IV (sustained operation) were exhaust temperatures, white smoke vs. time, and a continuous cylinder pressure trace. The injection quantity of the main charge during cold start test III was 96.5 mm^3/stroke.

TEST RESULTS

Figure 2 summarizes the starting characteristics of the five types of rotors tested in this investigation. Best results were obtained with the type E rotor. The following discussions refer only to the type E rotor to avoid a lengthy presentation.

oxygen for good start in the main chamber. At an optimized air-fuel ratio of 55:1, and 200°C charge air temperature, excellent start can be achieved in less than 5 seconds. Figure 8 illustrates the drop in charge temperature as a function of air-fuel ratio in the combustion aid at ambient temperatures of -10°C and +15°C. The starting time for the diesel Wankel engine with rotor E as a function of charge air temperature is shown in Figure 9.

SUSTAINED OPERATION - After the diesel Wankel engine has reached 110% of the cranking speed, the jaw clutch is disengaged and the engine is permitted to accelerate and reach a steady running speed. Figure 4 showed the combustion

Rotor	Type E
Injection Time	35° BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Quantity of Injected Fuel	96.5mm^3/stroke

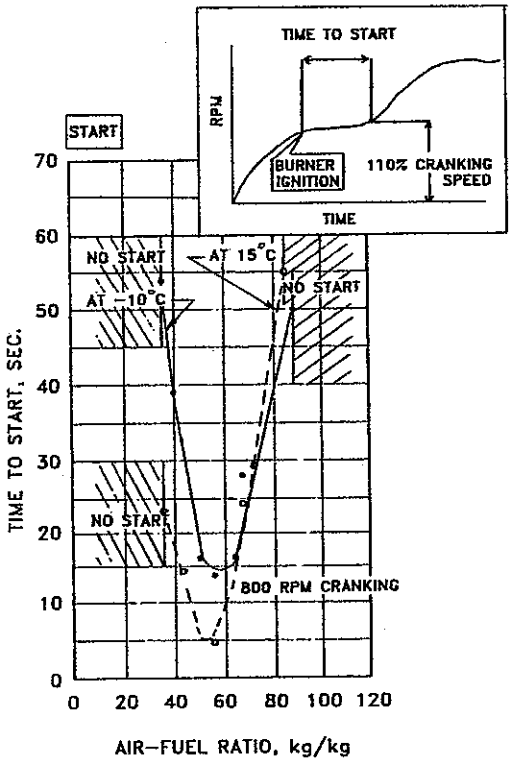
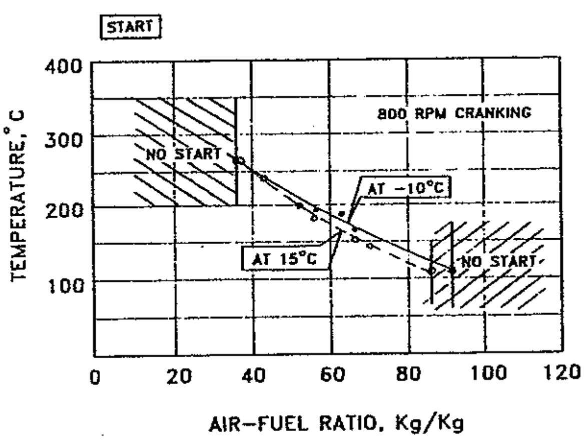


Figure 7. Effect of air-fuel ratio at burner on time to start.



Rotor	Type E
Injection Time	35° BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Quantity of Injected Fuel	96.5mm^3/stroke

Figure 8. Effect of air-fuel ratio at burner on temperature of charge.

Rotor	Type E
Injection Time	35° BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Quantity of Injected Fuel	96.5mm^3/stroke

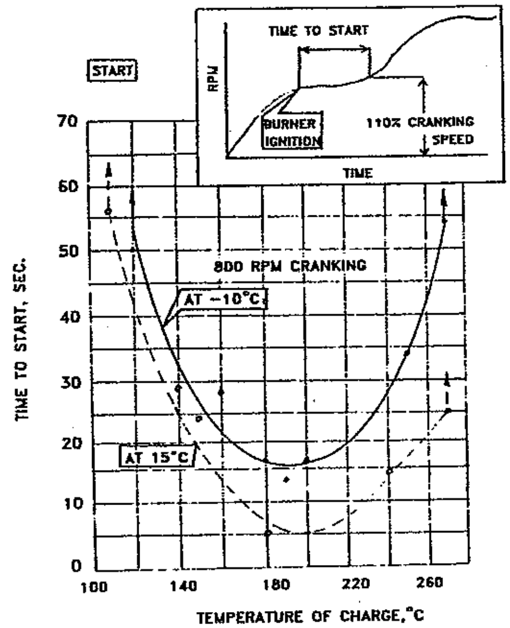


Figure 9. Effect of temperature of charge after burner on time to start.

pressure diagram for diesel Wankel installed with the type E rotor. The pressure traces at engine speeds of 1000, 2000, and 3000 rpm are shown in Figure 4.

Figure 10 shows the effect of combustion aid air-fuel ratio in the temperature of the inlet charge temperature, charge air oxygen content, and the exhaust gas temperature. It is noted as the air-fuel ratio is increased, the charge temperature drops, as well as the exhaust gas temperature. However, the oxygen content increases.

WHITE SMOKE - The white smoke situation in a diesel engine usually is a result of unburnt fuel. This condition exists when the ambient temperature of the engine temperature is still cold. Referring to two types of injectors (types D and E) shown in Figure 11, the white smoke emission as a function of time is shown in Figure 12. White smoke dissipation takes a long time as can be seen from Figure 12 after 120 secs. The small injection hole diameter between type D and type E nozzles is 0.15 mm hole vs. 0.25 mm hole. The smaller injection nozzle hole appears conducive to better white smoke suppression characteristics.

PROBLEMS - The initial tests of the cold start of the diesel Wankel engine showed two major problem areas. They are:

1. High cranking speed required to start diesel Wankel due to poor engine compression.

2. Excessive white smoke during engine idling condition.

Rotor	Type E
Injection Time	35° BTDC
Injection Opening Pressure	290kg/cm^2
Injector Holes	6x0.25mm
Quantity of Injected Fuel	96.5mm^3/stroke

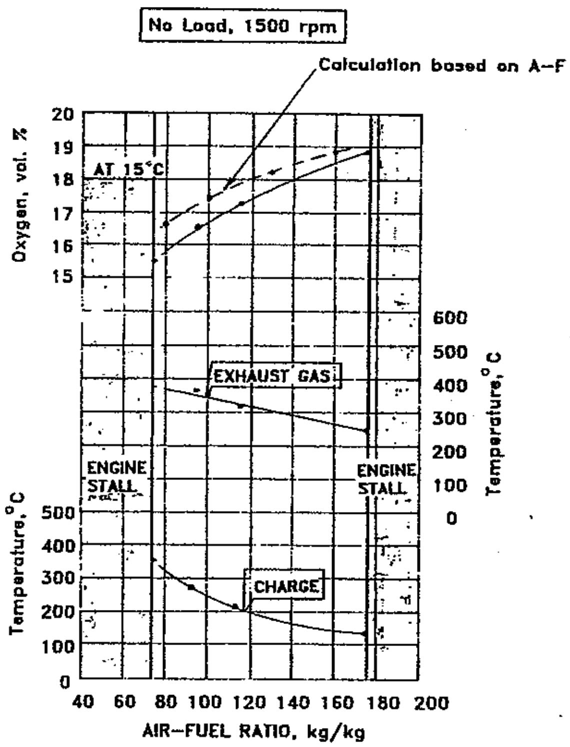


Figure 10. Effect of air-fuel ratio at burner on temperature of charge, oxygen content in charge and temperature of exhaust gas.

Today's modern material technology and designs could possibly overcome the poor sealing problem. An adiabatic Wankel engine would be ideal to overcome the cold start white smoke problem because of the rapid warm-up due to combustion chamber insulation.

CONCLUSIONS

This investigation has shown that by using optimized reciprocating diesel engine cold starting technology on the Wankel-type diesel engine, reasonably good results were obtained.

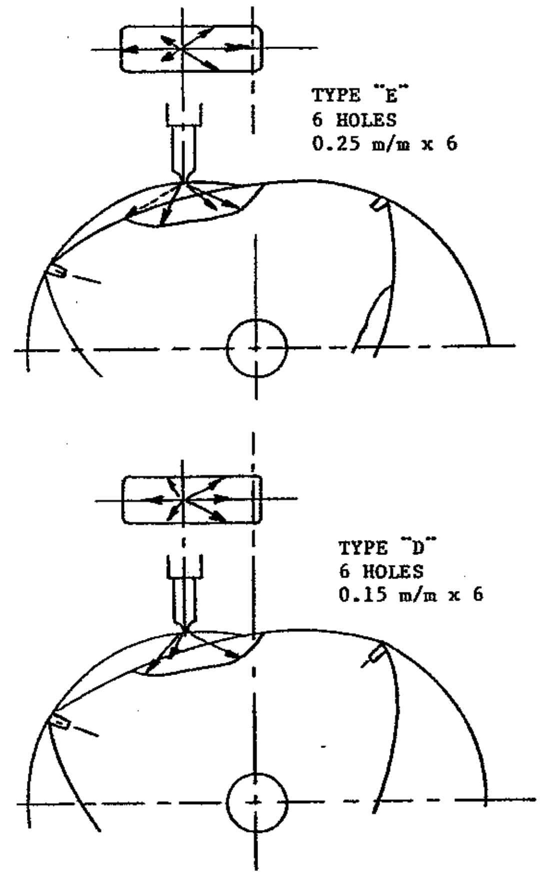


Figure 11. Two types of injector designs used for white smoke test.

However, some problems do exist and these should be solved. With the latest materials and rotary engine design progress, as well as the possible adiabatic Wankel design, these problems do not appear insurmountable. In conclusion, we can state:

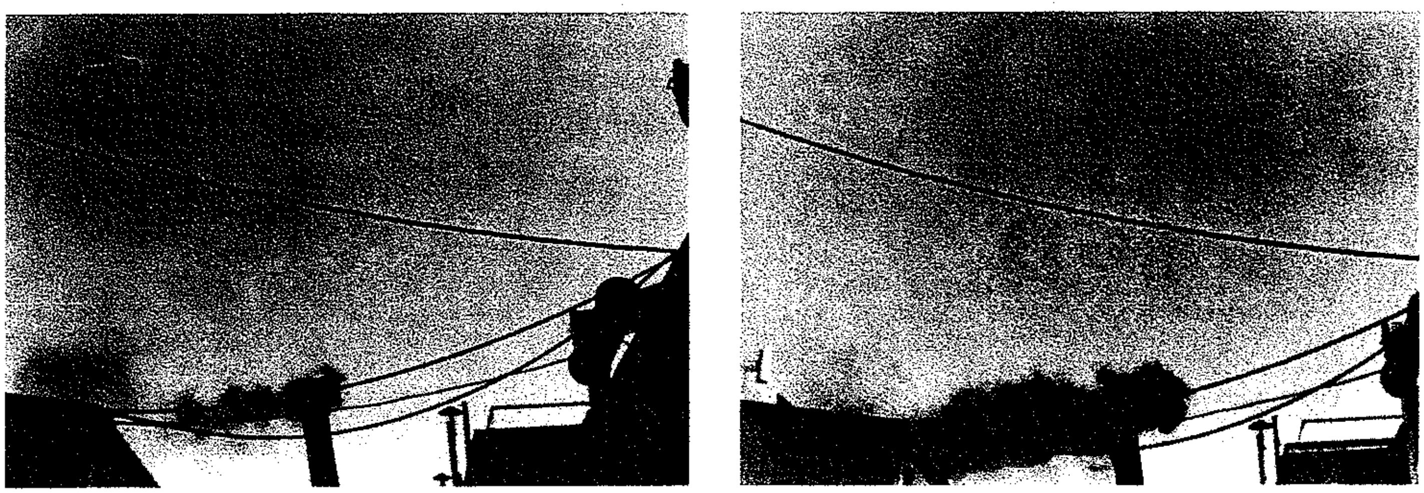
1. Feasibility of starting low compression ratio (10.5:1) single stage diesel Wankel-type rotary engine has been shown.

2. High crank speed requirements and white smoke emissions during no-load sustained operation are the two greatest drawbacks.

3. A variable rate heat input combustion aid is essential for cold start. A delicate balance between charge air temperatures and oxygen concentration must be accounted for. This is espeically true at low loads and higher engine speeds.

4. The compact type E rotor with six holes x 0.15 or 0.25 mm diameter showed the best start and operating conditions.

30 SEC.



TYPE OF INJECTOR:	"D"	120 SEC.	TYPE OF INJECTOR:	"E"
INJECTION TIME :	50° BTDC		INJECTION TIME :	35° BTDC
TEMP. OF CHARGE :	200°C		TEMP. OF CHARGE :	200°C

* Photo appears black, but is "white smoke."

Figure 12. White smoke emission of diesel Wankel at sustained operation.

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