AD-763 663

OPTIMAL ENGINE SELECTION FOR GROUND SUPPORT EQUIPMENT

William H. Womer, et al

Naval Air Engineering Center
Philadelphia, Pennsylvania

June 1973

AD 763 663

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Engines						
2. Wankel Engine						
3. Steam Engines						
4. Sterling Cycle Engines						
5. Stratified Charge Engines						
6. Gas Turbine Engines						
7. Electric Drive Systems						
8. Flywheel Systems						

AD 763 663

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Ground Support Equipment Department
Naval Air Engineering Center
Philadelphia, PA 19112

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

OPTIMAL ENGINE SELECTION FOR GROUND SUPPORT EQUIPMENT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Progress Report; July 1972 to June 1973

5. AUTHOR(S) (First name, middle initial, last name)

William H. Womer, Peter B. Zacharkiw

6. REPORT DATE

June 1973

7a. TOTAL NO. OF PAGES

~~52~~ 56

7b. NO. OF REFS

23

8a. CONTRACT OR GRANT NO.

A/T A3400000/051B/3F41461400

b. PROJECT NO.

Work Unit No. 05

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

NAEC-GSED-66

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Naval Air Systems Command
Washington, DC 20361

13. ABSTRACT

A comprehensive study was conducted to review the state-of-the-art of new prime movers and to determine if they could be applied to present or future ground support equipment (GSE). This investigation included a discussion of existing GSE prime mover requirements and the problems that they encounter.

1a

UNCLASSIFIED

NAVAL AIR ENGINEERING CENTER
PHILADELPHIA, PENNSYLVANIA 19112

GROUND SUPPORT EQUIPMENT DEPARTMENT

NAEC-GSED-66 JUNE 1973

CODE IDENT. NO. 28638

PROGRESS REPORT; JULY 1972 TO JUNE 1973
OPTIMAL ENGINE SELECTION
FOR
GROUND SUPPORT EQUIPMENT
AIRTASK NO. A3400000/051B/3F41461400,
WORK UNIT NO. 05

PREPARED BY William Wisner
Peter Zacharko

APPROVED BY

4ND-NAEC-5213/5100V 3/70

1c

1. TABLE OF CONTENTS

2. INTRODUCTION

Aircraft Ground Support Equipment (GSE) is being used more frequently in the Naval aviation environment. Tow-tractors, mobile air conditioners, electric power units, and many other items combine to form the large inventory of GSE in the U.S. Navy. Much of this equipment is powered by self contained internal combustion engines. Because these engines are subjected to extremely severe intermittent service, the high wear conditions that result create frequent maintenance problems. Besides wear problems, these powerplants have many other drawbacks, such as severe noise generation, vibration, high pollution levels, high logistics support costs, and low reliability, all of which greatly detract from the performance of the GSE they drive.

The Naval Air Engineering Center, Ground Support Equipment Department, is investigating the technology advances in the design of existing engines and innovative or recently developed powerplants. This investigation constitutes the first major step towards bringing the advantages of these advanced systems into the ground support equipment domain. The problems existent in present powerplants used in GSE are identified and the parameters being selected to determine the optimal prime mover are defined. A brief history and a description of the principles of operation for each candidate is given. The advantages and disadvantages of each proposed engine are discussed with respect to their present stage of development and availability.

Since many of the engine research programs are still in an early stage of development, technological breakthroughs are occurring constantly. For this reason, the following should only tend to serve as an introduction to the continuous work being accomplished in the field of powerplant research. Progress reports discussing the latest developments in this field will be published quarterly.

3. OBJECTIVES

This study was initiated to select a new prime mover for application to ground support equipment. This will be accomplished by determining the needs of GSE and then evaluating the prime mover candidates in the ground support environment. From the evaluation an optimal engine will be selected.

4. SUMMARY OF PROCEDURES AND RESULTS

4.1 Procedure. A literature search using the library facilities of NAEC, Widener College and the Defense Documentation Center resulted in many of the findings reported. Technical manuals for the different types of GSE were evaluated to determine the present requirements of the GSE prime movers. Visits and interviews with the agencies and companies listed in Appendix A helped to determine the present state-of-the-art of candidate GSE prime movers. The Naval activities listed provided an insight into the problems encountered with present engines.

4.2 Results. As a result of this investigation, it was determined that:

4.2.1 Four different types of prime movers are presently used in GSE. These have many drawbacks encompassing technical, logistical, and maintenance problems.

4.2.2 Gasoline and diesel engines comprise 78% of the GSE prime movers with the various horsepower requirements shown in Tables 8-2 and 8-4.

4.2.3 Seven major prime mover concepts are being investigated by various manufacturers and many of them would be feasible replacements for the present GSE engines. However, each is currently in a different stage of research and development.

5. CONCLUSIONS

5.1 Conclusions of Study. As a result of this investigation, the following conclusions can be made:

5.1.1 Excessive noise, vibration, and polluting emissions are just a few of the many problems existent in the prime movers currently used in ground support equipment. Excessive maintenance and the non-availability of repair parts are additional drawbacks.

5.1.2 Several expensive approaches are available to solve these problems. Noise and vibration can be reduced by placing the engines in noise dampening enclosures with better mounting systems to isolate them from the powered equipment. New repair parts could be manufactured to replenish depleted stocks. Emission levels could be reduced by adding catalytic converters and other control devices to the engine. The more practical and cost effective approach would be to replace the existing wide variety of engines with a more modern and efficient prime mover.

5.1.3 Certain prime mover candidates appear to be feasible and would meet the requirements of an optimal engine for present and future GSE. Several advantages of these systems are immediately apparent:

- The Wankel engine is about half the size and weight of a comparable gasoline engine.
- The Stirling engine has improved fuel economy with drastically reduced noise levels over conventional engines.
- Vibration is practically non-existent in the regenerative gas turbine and the multi-fuel capability of the Rankine cycle system is a desirable feature.

5.1.4 The remaining candidates have the advantage of being "pollution free," but retain disadvantages which outweigh their favorable characteristics as future GSE prime movers.

- The electric drive systems are bulky, heavy, and have long power source recharging times. These systems would not be as readily available for use as is normally required in the GSE environment.
- The flywheel systems are complex and would need an additional prime mover of their own to "rewind" the flywheel.

- The stratified charge engines do not reduce the problems associated with conventional engines and in fact, add to the problems with their increased complexity.

6. RECOMMENDATIONS

6.1 Recommendations Based on This Study. It is recommended that:

6.1.1 The investigation of the Wankel, Rankine cycle, Stirling, and gas turbine engines should continue until the optimal engine can be determined.

6.1.2 Prototype engines should be obtained and evaluated in the GSE environment to verify their acceptability and adaptability.

6.1.3 The further investigation of the electric drive, stratified charge, and flywheel systems should be limited to monitoring their development for any major breakthroughs.

6.1.4 Since the Wankel engine is already in mass production, its installation and evaluation in a piece of GSE was recommended and is scheduled to begin in FY 74.

7. LIST OF TABLES AND FIGURES

Tables Page

Figures

8. REPORT TEXT

8.1 GSE Prime Mover Problem Areas. The several different categories of prime movers which exist in the current ground support equipment inventory include internal combustion engines (gasoline or diesel type), gas turbine engines, and electric motors. All of these are used extensively throughout the Naval Aviation system, with the exception that gasoline engines are not used aboard aircraft carriers for safety reasons. Many of the problems which exist in these prime movers create an adverse effect on the performance of GSE they power. An optimal prime mover must be able to minimize each of these problems.

8.1.1 Vibration. Internal combustion engines have an inherent vibration problem due to their reciprocating motion. This vibration is the direct source of many failures in both the engine and the total piece of GSE. Vibration causes cyclic stresses and strains which lead to failure from fatigue. These failures reduce reliability and raise costs due to an increased need for maintenance. Vibration also affects the performance of certain pieces of GSE, such as aircraft weapons loaders. With their sophisticated hydraulic systems for handling ordnance, weapons loaders are expected to perform a lifting function with precision, but their performance is degraded because of the engine vibration.

8.1.2 Noise. Recently, much legislation has forced private industry to reduce the noise levels of its equipment. Similarly, BUMEDINST 6260.6B imposed noise level limits on equipment in the Department of the Navy. GSED Task Progress Report No. 72-7 concludes that not only can noise permanently damage the hearing of Navy personnel, but it produces a general loss of communications effectiveness as well. This report also indicates that the prime movers contribute greatly to the high level of noise being generated by GSE. Because of the dangers involved, a new prime mover must be able to comply with the recommended noise standards.

8.1.3 Weight. A savings of weight in almost any unit would show many advantages. Up to 2000 pounds per unit could be saved through the use of a new prime mover. This weight reduction would be obtained through the use of a lighter engine. By using a lighter engine, the weight of the supporting structural members would also be reduced. On the deck of an aircraft carrier where about sixty pieces of GSE are used, over 20,000 pounds could be saved. Then too, the cost of shipping GSE between Naval facilities could be reduced since shipping costs are proportional to weight.

8.1.4 Size. Because of the limited dimensions of the work areas on a ship, every cubic foot of space is important. Since the large size of most pieces of GSE is a direct result of its bulky engine, a new prime mover should produce a decrease in the volume of the new unit. Substantial savings in both space and cost would result from a reduction in the volume of GSE.

8.1.5 Fuel Economy and Restrictions. Because of the space problem on a carrier, the amount of fuel needed by GSE should be minimized. A new prime mover which uses less fuel while producing the same level of performance would be a desirable feature. A savings in both cost and space would result if the GSE used on a carrier required less fuel. An additional requirement for a new prime mover is that it be able to run on heavy distillate fuels which are normally available on a ship. A prime mover which could operate only on gasoline would be disadvantageous because gasoline is considered unsafe to store on shipboard.

8.1.6 Reliability and Maintainability. Better reliability and less need for maintenance would show a substantial cost savings. Many new prime movers contain up to 50% fewer parts than existing engines and require much less periodic servicing. Thus, these new prime movers would be expected to be more reliable.

8.1.7 Costs. Although the initial appropriation cost of a diesel engine is about four times as much as the cost of an equivalent gasoline engine, many pieces of GSE are procured with diesel engines almost entirely because of the fuel constraints existent in shipboard operations. Because of the decrease in size, a multi-fuel capability, and the reduced number of moving parts in several of the newer prime movers, costs could be reduced both in initial procurements and in later repair parts logistical support.

8.1.8 Emissions. Some government regulatory agencies have established maximum pollution standards for industrial engines and equipment. While these standards cannot directly be applied to the Department of Defense, it can be expected that future statutes, when enacted, will be similar in nature. Since DoD equipment can be expected to comply with these regulations, any new prime mover candidate must be as pollution free as possible.

8.2 Existing Prime Movers. Present ground support equipment uses four different types of prime movers for power. The majority use gasoline or diesel-powered, internal combustion engines (Figure 8-1). Some units use gas turbine engines while the remainder use an electric drive system with power supplied through a cable.

8.2.1 Gasoline Engines. The gasoline engines used in ground support equipment range from 25 to 250 horsepower (Figure 8-2).

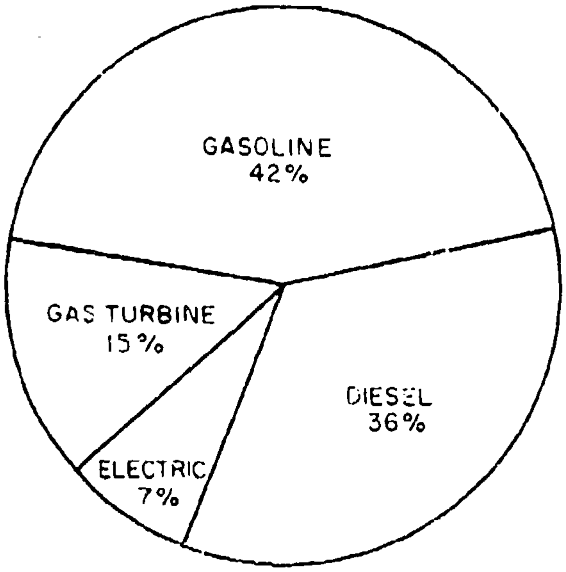

Figure 8-1. Prime Mover Distribution in GSE

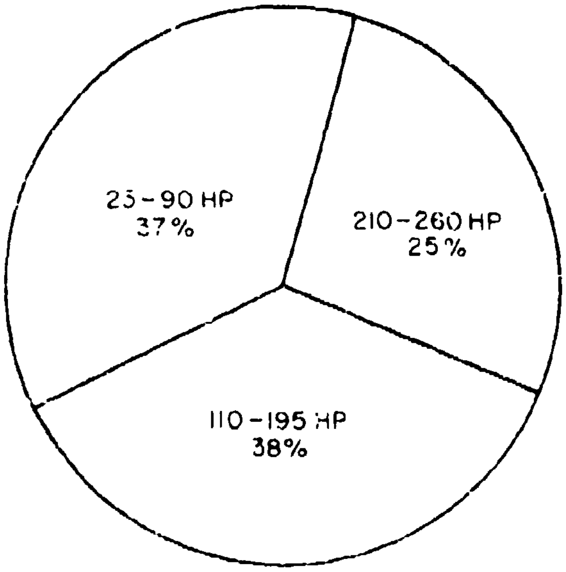

Figure 8-2. Gasoline Engine Horsepower Distribution

Six different manufacturers supply gasoline engines for use in ground support equipment (Figure 8-3). Each manufacturer also supplies several different models to suit the various requirements of GSE (Table 8-1).

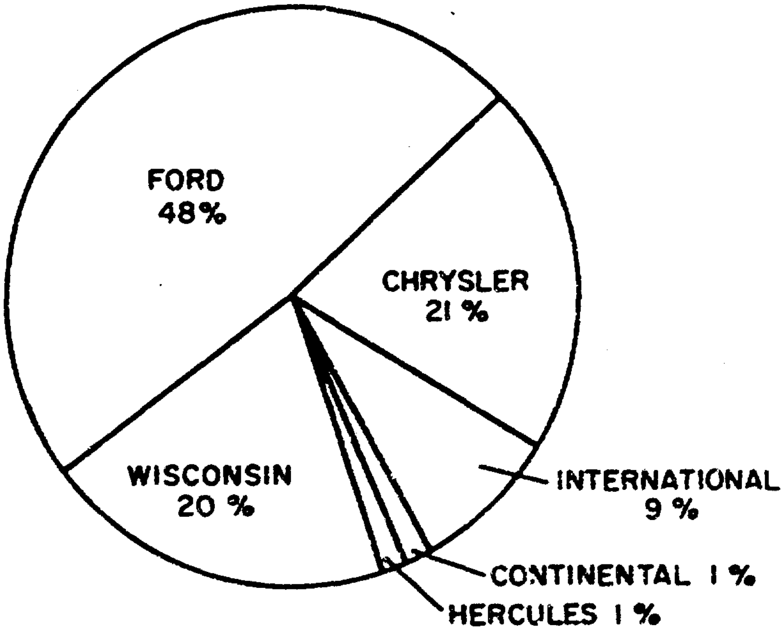

Figure 8-3. Distribution of Gasoline Engines by Manufacturer

An engine malfunction and failure analysis was made for selected gasoline engines over a two year period. These malfunctions are indications of strictly internal combustion engine failures and not failures of starting motors, carburetors, or other engine accessories (Table 8-2).

8.2.2 Diesel Engines. The diesel engines used in ground support equipment range from 25 to 290 hp, with the majority in the 100-150 hp range (Figure 8-4).

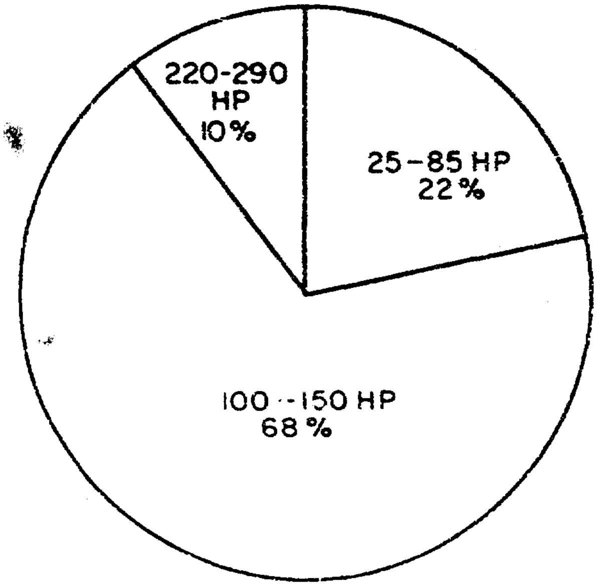

Figure 8-4. Diesel Engine Horsepower Distribution

TABLE 8-1
GASOLINE ENGINE SPECIFICATIONS

Total Gasoline Engines - 3583

Manufacturer	Model Number	GSE Application	Type	Number of Active GSE*	Horsepower @ rpm	Torque @ rpm
Ford	JB-317	NB-1; NC-5, 5A	8-cyl	589	155 @ 3000	270 @ 3000
	JB-332	NC-5B	8-cyl	300	170 @ 3000	297 @ 3000
	B6PL6005E	NC-7, 7A	8-cyl	178	165 @ 2765	306 @ 2600
	B78L6007A	NC-7B	8-cyl	50	165 @ 2765	306 @ 2600
	302GP6001HW	TA-75	8-cyl	602	210 @ 4400	250 @ 4400
Wisconsin	MVD-4D	P5R15GA/B	4-cyl	224	25 @ 2400	55 @ 2400
	MVF-4D	515HG[illegible]4R15G-B; 515HGP3MS[illegible];A/S32K1	4-cyl	460	25 @ 2400	55 @ 2400
	MVG-4D	P5R	4-cyl	38	25 @ 2400	55 @ 2400
	MVH-4D	A/S32K1	4-cyl	8	27 @ 2400	60 @ 2400
Hercules	IXLB-5	NR-1	4-cyl	1	N/A	N/A
	IXLB-3	NR-1	4-cyl	21	34 @ 2400	73 @ 2400
	QXLD-3	MD-2	N/A	18	N/A	N/A
Chrysler	IND-31	NR-1A	6-cyl	-	7[illegible] @ 2300	166 @ 2300
	IND-32	MD-2; JG-75	6-cyl	665	88 @ 2800	165 @ 2800
	56/56A	NR-3	V-8	12	120 @ 2500	252 @ 2500
	IND-30	ME1/1A	6-cyl	2	N/A	N/A
	HT413-500	TA-18	8-cyl	61	N/A	N/A
Continental	BA-427	NR-3A	6-cyl	20	112 @ 1800	326 @ 1800
	ES-415	P6R80GXA	6-cyl	8	82 @ 1850	234 @ 1850
	FS-244	ME-1/1A	N/A	16	N/A	N/A
International	V-401	TA-18	V-8	299	195 @ 3200	355 @ 2[illegible]0
	V-549	TA-30	V-8	11	256 @ 3400	500 @ 1880

*Extracted from 3M data for April 1973

TABLE 8-2
GASOLINE ENGINE MALFUNCTION SUMMARY*

Summary by Malfunction

Malfunction Description Code	Malfunction Description	Number of Failures
374	Internal Failure	24
181	Compression Low	18
710	Bearing Failing or Faulty	18
399	Excessive Oil Consumption	14
142	Engine Removed, Excessive Maintenance	13
020	Worn, Stripped, Chafed or Frayed	12
381	Leaking, Internal or External	10
135	Binding, Jammed, or Stuck	9
070	Broken	6
008	Noisy	3
900	Burned or Overheated	2
503	Sudden Stop	1
537	Low Power	1
525	Incorrect Pressure	1
730	Loose	1
	Total	133

Summary by Manufacturer

Engine Manufacturer	Current Inventory	Number of Failures	Number of Failures Per Hundred Units
Chrysler	782	53	7
Ford	821	60	6
Wisconsin	710	29	4
International	329	1	.3

*This information is based upon 3-M Data for a selected group of common types of engines for the twenty-four month period of January 1971 through January 1973.

Although six different manufacturers are used to supply the Navy with the diesel engines used in GSE, Detroit Diesel produces 50% of this total (Figure 8-5). While the power ratings of these engines are similar to those of the gasoline engines, the majority of the diesel powered pieces of GSE are used in shipboard applications (Table 8-3).

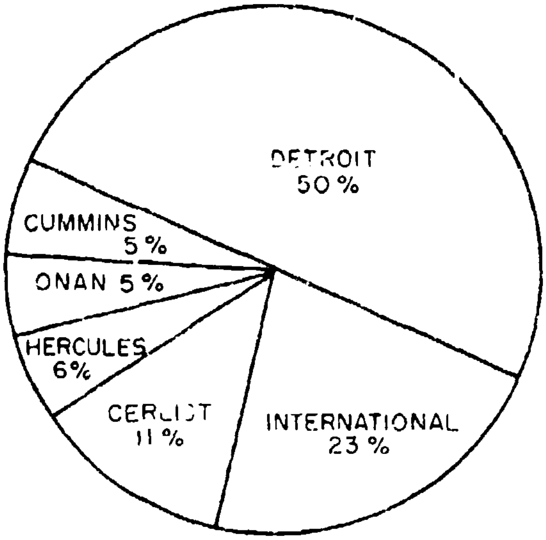

Figure 8-5. Distribution of Diesel Engines by Manufacturer

The failure analysis for the diesel engines shows them to be more reliable than the comparable gasoline engines (Table 8-4). These malfunctions are strictly engine failures and, again, not those of the associated accessories.

8.2.3 Gas Turbines. Gas turbine engines are used in ground support equipment when high volume air movement is required. The most common GSE use of gas turbine engine is in air start units. This is because of the high volume of air required to start modern turbine powered aircraft. The approximately 1200 gas turbines used in GSE are supplied by the AiResearch Manufacturing Company.

8.2.4 Electric Drive Systems. Ground support equipment which use electric drive systems are employed whenever a reliable power supply is available. These units normally operate from a 440VAC power source. The two main factors which limit their use are the availability of a reliable power source and the amount of cable available to remotely locate these units from a power outlet.

TABLE 6-3
DIESEL ENGINE SPECIFICATIONS

Total Diesel Engines - 3066

Engine Manufacturer	Model Number	GSE Application	Type	Number of Active GSE*	Horsepower @ rpm	Torque @ rpm
Detroit	3-71	NB-3	3-cyl	194	106 @ 2100	293 @ 1400
	4-53	NC-2A; NC-8A	4-cyl	1020	140 @ 2800	295 @ 1800
	6-71	NC-10A, B, C	6-cyl	163	220 @ 1846	625 @ 1846
	6V-71	NR-8	6-cyl	54	238 @ 2100	649 @ 1400
	8V-71	NC-12A	8-cyl	100	290 @ 2100	805 @ 1200
Hercules	D298ERTX22	NR-10	6-cyl	190	82 @ 1800	239 @ 1800
	D1700	MD-1/1A	N/A	4	N/A	N/A
Onan	DJ-60	Aero-46A/A1	4-cyl	8	25 @ 2400	54 @ 2400
	DJ-120	Aero-47A/A1	4-cyl	137	28 @ 2400	62 @ 2400
International	UD-282	MD-3	6-cyl	692	100 @ 3000	204 @ 1800
Cerlist	Mod-3	AHT-64	3-cyl	341	85 @ 3000	170 @ 1900
Cummins	NH-200	NC-10	6-cyl	163	146 @ 1846	415 @ 1846

*Extracted from 3M data for April 1973

TABLE 8-4
DIESEL ENGINE MALFUNCTION SUMMARY*

Summary by Malfunction

Malfunction Description Code	Malfunction Description	Number of Failures
351	Leaking, Internal or External	16
374	Internal Failure	12
181	Compression Low	4
020	Worn, Stripped, Chafed or Frayed	4
135	Binding, Jammed or Stuck	2
710	Bearing Failing or Faulty	1
399	Excessive Oil Consumption	1
503	Sudden Stop	1
190	Cracked	1
	Total	42

Summary by Manufacturer

Engine Manufacturer	Current Inventory	Number of Failures	Number of Failures Per Hundred Units
Onan	137	6	4
International	692	18	3
Detroit	1484	17	1.2
Hercules	190	1	.5
Cummins	163	0	
Cerlist	341	0	

---

*This information is based upon 3-M Data for a select group of common types of diesel engines for the twenty-four month period of January 1971 through January 1973.

8.3 Prime Mover Candidates. Seven major types of prime movers were investigated as possible replacements for present GSE engines. The following sections discuss the principles, development, problem areas, advantages, and disadvantages of each of the candidates. A compilation of the characteristics of each is included as a source of comparison.

8.3.1 Rotary Combustion Engines.

8.3.1.1 Principles. The rotary combustion engine is an internal combustion engine which operates on the four stroke or Otto cycle consisting of intake, compression, combustion, and exhaust. The example of this type which has received more attention and development effort than any other is the Wankel engine. Basically, it employs a three-lobed rotor which turns inside an epitrochoidal surface. It normally uses gasoline for fuel in the four stroke cycle, but has experimentally been modified to operate on other fuels in a diesel version. Valving of the air-fuel charge and exhaust gases is accomplished through ports uncovered in sequence by the rotor. This process can easily be compared to a conventional, piston driven, spark-ignited engine (Figure 8-6).

An air-fuel mixture is sucked in through the intake port on the Wankel and through the intake valve opening on the piston engine in the first stroke. The compression of this mixture to higher pressure and temperature occurs on the second stroke. A spark from the spark plug initiates the combustion and expansion process that occurs on the third or power stroke. Finally, this burnt mixture is pushed through the exhaust port on the Wankel and through the exhaust valve opening on the piston engine to complete the cycle and the fourth stroke. Also by way of comparison, the piston engine produces one power impulse for every two revolutions of the crankshaft while the Wankel produces three power impulses for each revolution of the rotor.

8.3.1.2 Development. In 1926, Dr. Felix Wankel, a German engineer and inventor, began a systematic investigation of rotary engines and in the 1930's, established a research institute to further his investigation. Within a few years, he was able to conclude that the successful development of a rotating engine required the solution of three problems—geometry, sealing, and porting.

Wankel's initial mechanical concepts were complex and involved. Later, when NSU of Germany took an interest in his project, Dr. Walter Froede of NSU became involved. It was through his efforts that Wankel's original concept was developed into an engine. However, the engine was still plagued with many problems when it finally became operational in 1956.

The development of the rotary engine was given a major boost when the Curtiss-Wright Corporation purchased the North American manufacturing rights to the Wankel engine in 1958. Under the direction of Dr. M. Bentele and Mr. Charles Jones, the engine was developed to the point that its potential became evident. General

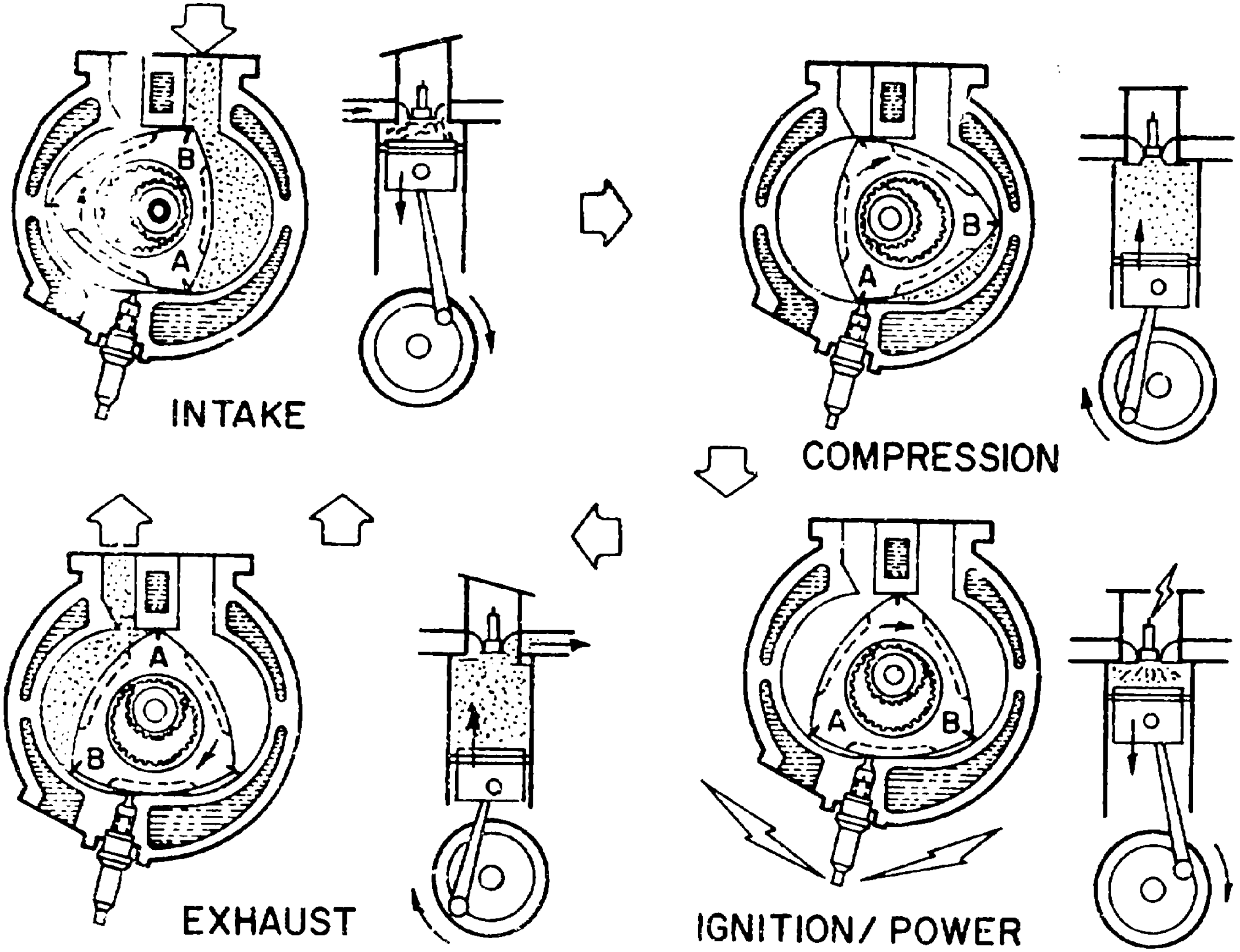

Figure 8-6. Otto Cycle Wankel vs. Piston Engine Comparison

Motors and Outboard-Marine Corporation have now joined Curtiss-Wright as U.S. licensees, and nearly every major engine manufacturer in the world either holds a license to manufacture the Wankel, is negotiating for one, or is independently developing its own rotary engine.

8.3.1.3 Problem Areas. Every piece of machinery, no matter how simple or complex, encounters problems during its development and the rotary engine was no exception. The major rotary engine problem areas of geometry, sealing, and cooling are discussed in the following sections.

8.3.1.3.1 Geometry. Rotary engines can have a variety of designs, some of which are shown in Figure 8-7.

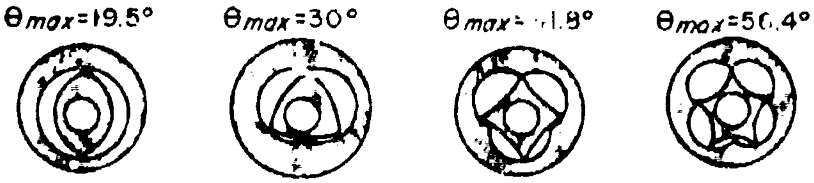

Figure 8-7. Rotary Engine Geometry

These designs, along with others, were studied extensively. Many parameters had to be investigated with optimization occuring in such areas as the compression ratio and the "leaning angle" of the apex seals. The leaning angle, theta (θ), is that angle through which the apex seal varies from the perpendicular with respect to the rotor housing or working surface (Figure 8-8). The apex seal continuously varies within 30° of the normal and is perpendicular to the working surface only when it crosses the major and minor axes.[17]

The maximum "leaning angle" occurs at the point of greatest variation from the perpendicular between the rotor and the working surface. Through extensive investigation it was determined that acceptable seal life could be obtained if the maximum allowable "leaning angle" was 30°. Because the compression ratio is determined by the geometry of the combustion chamber, extensive research was required to design the chamber so that it would be compatible with today's fuels. It was decided that the three lobed rotor with a 30° "leaning angle" was the best suitable choice.

8.3.1.3.2 Sealing. The most crucial of all the problems that prevented the efficient operation of the Wankel engine during the early stages of its development concerned sealing the working chambers to prevent gas leakage between them. The several paths that must be blocked exist across the apices between the rotor faces, and around the sides of the rotor faces. These seals, known as the apex seal and the side seal respectively, are shown in Figure 8-9.

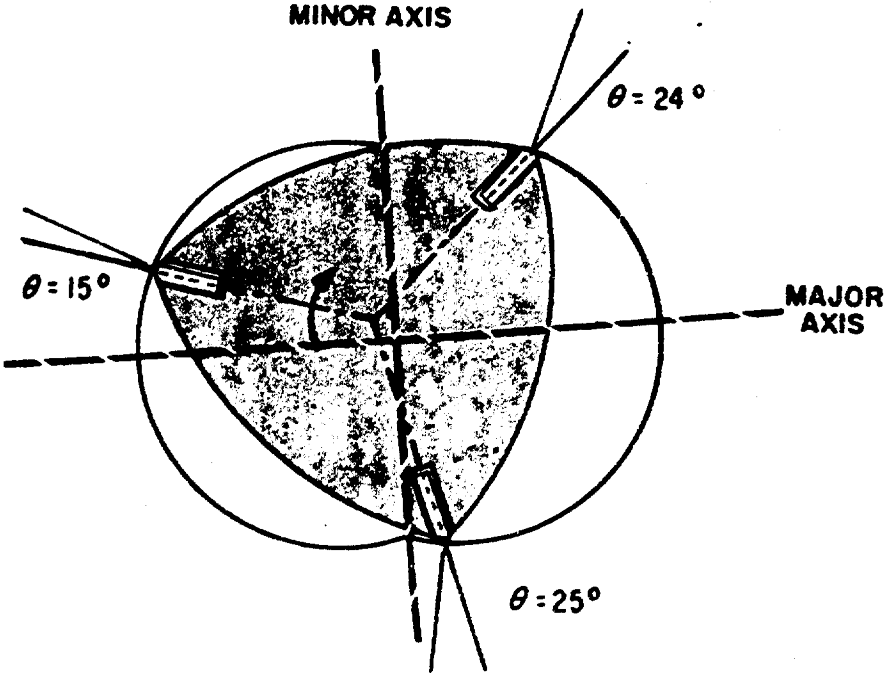

Figure 8-8. Seal Leaning Angles in a Wankel Engine

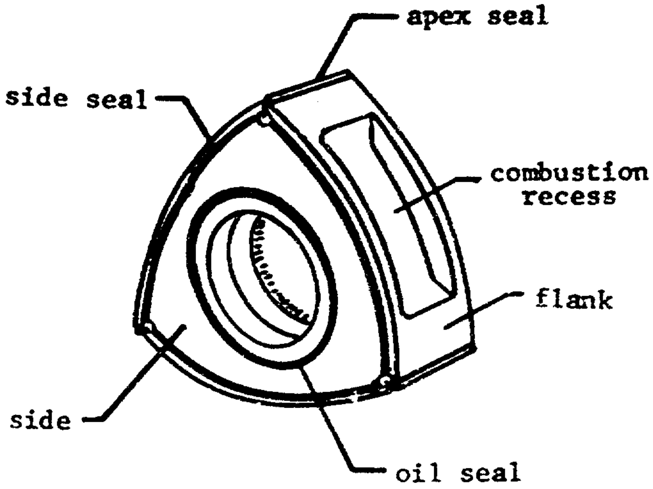

Figure 8-9. Typical Wankel Engine Rotor Seals

The performance of the seals in the Wankel engine is determined by the many variables in the design of the engine, such as the basic configuration, the materials and dimensions of the sealing elements, the lubricating conditions, the rotor and rotor housing cooling conditions, and the precision of the machining and finishing of the surfaces facing the seals. The length of the gas leakage paths, the size of the oil seal, the number of clearances, the configuration of the seals, and their operating conditions constitute serious disadvantages to the proper design, manufacture, and operation of this engine. As a result, it is undeniable that the gas sealing efficiency of the Wankel engine is unfavorable, especially at low speeds.[17]

Sealing consists of providing uninterrupted contact over the whole primary and secondary sealing areas. The primary areas are those between a seal and a stationary surface, the seal being carried in a moving component. The secondary sealing areas exist between the seal and its slot, groove, or bore. Sufficient force must be applied to the sealing element at all times to maintain contact. Keeping this sealing force constant was a problem with the Wankel because of the high leaning angles encountered. After much development and many modifications, this problem is now considered to be solved. Three of the stages in the development of the sealing system used in the Curtiss-Wright Wankel are shown in Figure 8-10. The final configuration is depicted on the right.[10]

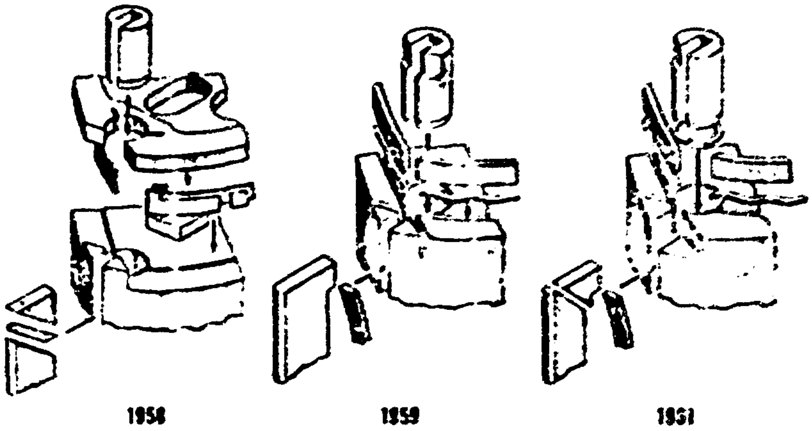

Figure 8-10. Progressive Stages of Apex Seal Development

Apex seal wear probably constituted the major Wankel engine seal problem. The materials used to make the seal had such a high wear rate that the Wankel engine was almost considered to be impractical. Only recently has advancing technology produced a more suitable seal material which could decrease the rate of wear to acceptable levels.

8.3.1.3.3 Cooling. Like the reciprocating piston engine, the Wankel engine can be adapted to either air or liquid cooling, but the cooling problems are strikingly different. The basic duty of the housing cooling system is to lower the temperature of the areas exposed to the highest heat input and to minimize the temperature differences throughout the housing.

Certain stationary areas on the working surface are always exposed to the same phase of the operational cycle, therefore the heat distribution in the housing is uneven. A cooling problem exists only in the area immediately surrounding the spark plugs where combustion and expansion takes place. The rest of the working surface requires little cooling. This uneven heating causes distortion of the housing which can prevent the gas and oil sealing elements from functioning properly.

After much investigation, these cooling problems were solved by using new, high-conductivity materials for the rotor housing, and by coolant circulation methods that match the cooling capacity of each location with the distribution of heat throughout the housing. As a result, the coolant flow velocity is high in the hot areas of the housing and lower in others. This system assures even heat dissipation and permits balanced cooling with large, clog free, easily manufactured passages.[17]

The exhaust gas temperatures of the Wankel engine average about 250 Fahrenheit degrees hotter than conventional reciprocating engines. This important consideration means that certain emission control devices would be more effective in reducing carbon moxoxide (CO) and hydrocarbon (HC) emissions to acceptable levels.

8.3.1.4 Advantages and Disadvantages. The Wankel engine's strongest claim is its large power output from a small, light package (Figure 8-11). Its size is about half that of an equivalent reciprocating piston engine and its weight is less than half. By avoiding the use of reciprocating members such as pistons and connecting rods, the Wankel engine operates with minimal vibration and is easily balanced. The difference in the total number of parts in the two engines is significant. A representative piston engine has 1029 parts while a Wankel of the same power has 633. This fewer number of parts decreases both the costs and the complexity of the Wankel engine (Figure 8-12).[9]

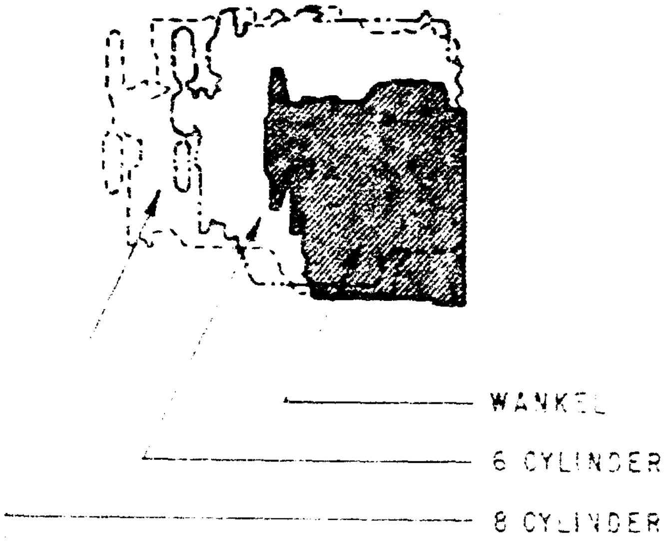

Figure 8-11. Comparison in Size for Same Horsepower

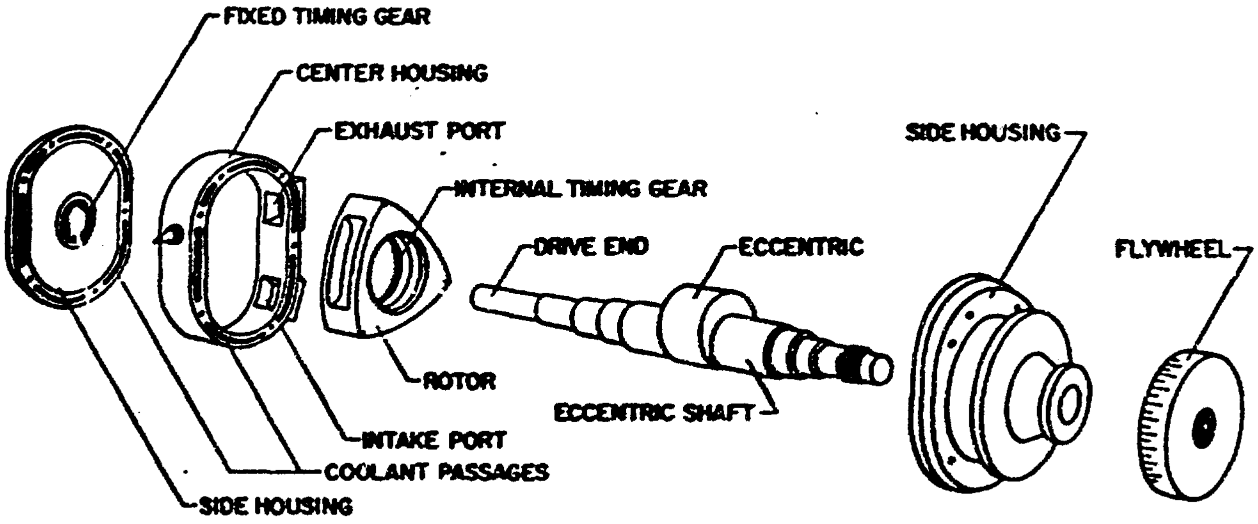

Figure 8-12. Basic Components of the Wankel Engine

The Wankel engine is not without its disadvantages. Although the seals have been developed to an acceptable level of performance, much work is still needed to increase their level of reliability to that of a diesel engine. Emission standards for CO and HC can be met by the Wankel, but nitrous oxides (NO_x) are still higher than acceptable. The major disadvantage is that the fuel economy of the Wankel engine can be up to 40% worse than that of a conventional reciprocating engine. Also, in presently available engines, gasoline is the only fuel that can be used for operation.

8.3.2 Gas Turbine Engines.

8.3.2.1 Principles. Derived from aircraft turbo-jet powerplants, the gas turbine is a continuous combustion, high speed heat engine. In elemental form, it functions in the following manner (Figure 8-13). A compressor takes in ambient air and feeds it to a combustor can where fuel is added. The ensuing combustion process produces hot, high pressure gases, which expand through the compressor turbine. A small amount of work is extracted by the turbine to power the previously mentioned compressor section. The remaining work is removed as this hot gas expands to atmospheric pressure in the power turbine. The shaft of this turbine is the power output shaft for the engine. A common improvement to this basic cycle is made with the addition of duel regenerators which recover waste heat from the exhaust and add it to the combustor inlet air.[6]

8.3.2.2 Development. Gas turbines were developed towards the end of World War II in response to a need for higher power aircraft engines. These engines produced exhaust thrust as their only useful power. After the war, efforts were put forth to redesign this device to yield rotary power via a shaft. By the 1950's, small experimental turbines had been built and tested in vehicles but with disappointing results. Poor fuel economy, noise, and a lag between throttle actuation and vehicle acceleration made them undesirable.

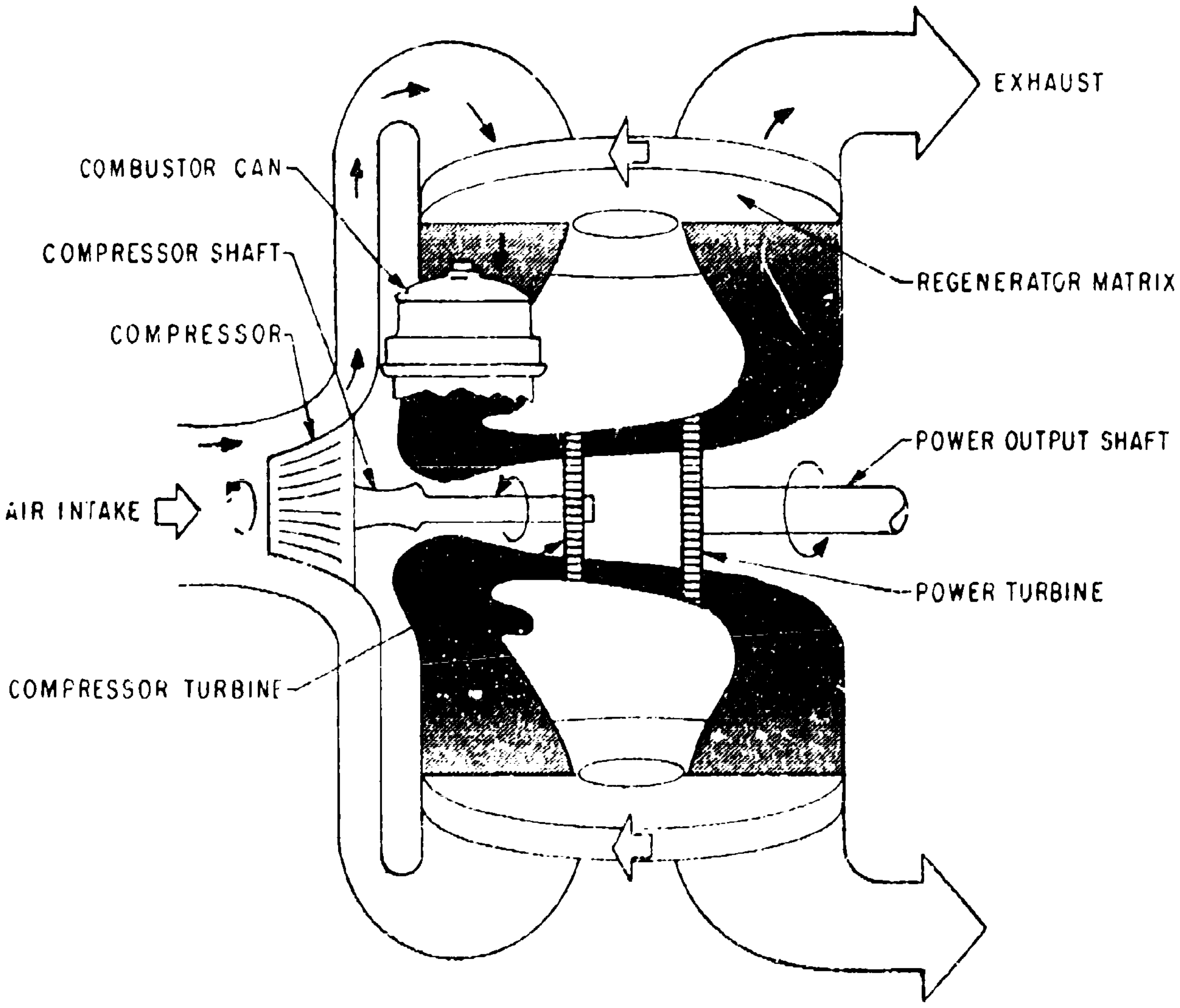

Figure 8-13. Gas Turbine Engine Functional Description

The push for low-pollution power led to the rediscovery of turbines in the late 1960's as possible replacements for conventional piston engines in autos and trucks. The engine became even more attractive when acceleration lag was reduced and more advanced construction materials lowered the costs.

At present, several manufacturers are developing their own versions of the gas turbine. Many have characteristics of power, weight, volume, etc. that make them entirely suitable for vehicle use. Chrysler Corporation has a fleet of prototype automobiles which are being evaluated for performance. The EPA is financing a portion of this project as well as different projects with other manufacturers. However, ground vehicle turbine production is presently limited to the 300-500 HP range.

8.3.2.3 Problem Areas. While most of earlier troubles associated with aircraft turbine engines have already been corrected, the development of a smaller turbine for use in small or automobile type applications has created many new problems.

8.3.2.3.1 Costs. The most persistent problem in any turbine design has been its high cost. The continuous high temperatures generated within these engines require the use of exotic and expensive heat-resistant metallic alloys. The basic engine design also necessitates costly precision machining of the complex turbine blade and guide vane shapes.[2] Material researchers hope to solve these metallurgical problems by developing inexpensive ceramic composites which can be cast and finished to final dimensions in a few simple operations. Current aircraft industry estimates place the future cost of large production runs of automotive-sized turbines at three times the present cost of conventional piston engines.

8.3.2.3.2 Fuel Economy. Gas turbine fuel economy has never been able to match that of similar sized piston engines.[4] Development is continuing to improve the performance of the compressor, turbine, and regenerator, which should improve fuel economy. Other possible ways to improve fuel economy include: increasing the turbine inlet temperature, using water injection, and optimizing the transmission.[3]

8.3.2.3.3 Emissions. Low CO and HC emissions are the prime reason the automotive industry is interested in the gas turbine. However, its oxides of nitrogen output is not especially favorable. The high temperature combustion conditions allow the nitrogen to combine with the oxygen present in the atmospheric air to form these oxides. Research has been initiated to develop new combustors which will lower the NO_x emissions without affecting the already low HC and CO emissions.[4, 23]

8.3.2.4 Advantages and Disadvantages. The most outstanding advantage of the gas turbine engine is its incredible reliability. Many turbines are currently running in continuous, unattended operation, doing such jobs as generating electricity and pumping fuels in isolated locations. Properly maintained, these units almost never have unexpected failures. Lengthened maintenance intervals and increased engine life expectancy may well outweigh the higher initial cost of these powerplants.

Engine simplicity is the key to reliability. Fuel delivery is accomplished by a simple pump and spray nozzle arrangement. A rudimentary ignition is used but only for start-up purposes. Almost any liquid or gaseous non-leaded fuel may be used, including jet fuel, gasoline, alcohol, and natural or LP gas. The lack of reciprocating parts makes vibration almost non-existant. This in turn, diminishes the need for strengthened frame members and engine mounts to absorb the destructive harmonic vibrations normally associated with reciprocating engines.

Although the gas turbine itself is very simple, the control systems needed to regulate it are very complex. Fuel must continuously be metered into the combustor cans in correct amounts to obtain the desired speeds. Exhaust temperatures must be monitored for indications of overstressing. Interlocking fuel-ignition-starter motor controls are required to prevent hazardous flaming "hot starts" in the event of delayed ignition after prolonged cranking. These controls are expensive and must be manufactured to very close tolerances.

The major disadvantage of the gas turbine is the high initial cost. For a 120 HP system, the present cost would be between $13,000 and $20,000. However, with future refinements and new materials, the cost could be reduced considerably.

8.3.3 Rankine Cycle Systems.

8.3.3.1 Principles. The Rankine-cycle power system is an external combustion engine in which high-pressure steam, or some alternate working fluid vapor, is expanded in either a turbine or a positive displacement (piston-type) expander to produce work. As shown in the schematic diagram (Figure 8-14), a high pressure pump (A) draws liquid, initially at a low pressure, from the reservoir (E) and forces it under high pressure through the vapor generator (B). It is converted to superheated vapor by heat transfer from the heat of combustion in the burner. The hot, high pressure vapor is then metered into an expander (C) through a flow control valve. The vapor then expands, lowering its pressure and temperature, and is converted back to a liquid in a condenser (D), which is typically air cooled. The resulting low-pressure liquid can then be returned to the vapor generator by the pump completing the cycle.[20]

All Rankine cycle engines use the same basic scheme with the major design variations being the expander which can be either a turbine or piston type unit.

8.3.3.2 Development. The use of Rankine cycle engines in vehicles dates back to 1827 when primitive steam engines were used to power coaches. Most of the early steam engines had a large water boiler and used a noncondensing, single-expansion engine. Necessitated by the nature of the system, the large quantities of water required as much as a half-hour of heating for the engine to become operable from a cold start.

Since that time, additional development has produced two different approaches, a steam turbine and a steam reciprocator. Of these two, more development has gone into the piston or reciprocating types. The Williams Engine Company, Ambler, Pennsylvania, has worked on a reciprocating type since 1899. Other companies, such as Thermo-Electron (TECO) and Steam Engine Systems (SES), both from Massachusettes, have recently developed their own versions of a reciprocating steam engine.

Two other companies, Aerojet General Corporation, and Lear Motors Corporation, have each developed a vapor turbine engine, using a turbine for the expander. Two engines have been developed by Lear, a 120 and 240 horsepower system. These power systems are basic and simple in design, using a vapor generator (boiler), a steam expander (single stage turbine), a regenerator, and a condenser in a closed-loop cycle (Figure 8-15). A high degree of flexibility is available in this system, since the separate components can be installed independently of each other. The uniqueness of the Lear system lies primarily in its compact size, low emission and diminished noise characteristics, and its adaptability to many applications.

The Lear vapor turbine system has been successfully tested in a bus for the California Steam Bus Demonstration Project. The Lear engine is one of the four Rankine cycle engines which will undergo a strict 200 hour test program in early 1973 for the Environmental Protection Agency (EPA) to determine its emissions, performance, and durability over its entire operating range. A comparison between the different systems is shown in Table 8-5.

8.3.3.3 Problem Areas. Throughout the development of the Rankine cycle engine, many problems plagued its progress. Many of the problems which seemed insurmountable have now been reduced to workable solutions. These problems are defined and discussed in the following sections.

8.3.3.3.1 Condenser. Because of the limited heat transfer technology available in the past, the relatively large size of the condenser presented a critical problem in former Rankine cycle power system applications. As a result, the frontal area, volume, and fan horsepower requirements for condensers have been excessively large. These have been strong factors in limiting the application of the Rankine cycle system. As a result, the AiResearch Manufacturing Company, California, developed new heat transfer designs and techniques to permit the use of condensers comparable in size to that of the present automobile radiator. The solution resulted in the use of perforated fins which reduced the condenser size by a factor of two over previous designs. This reduction in condenser volume not only minimized installation problems, but also yielded a comparable savings in material costs.[1]

8.3.3.3.2 Vapor Generator Assembly. The vapor generator consists of the combustion blower, the combustor, and the boiler tube bundle. Although a number of boilers have been designed and tested by different manufacturers, continued development of a compact vapor generator, without compromising its low emission performance, is still progressing.

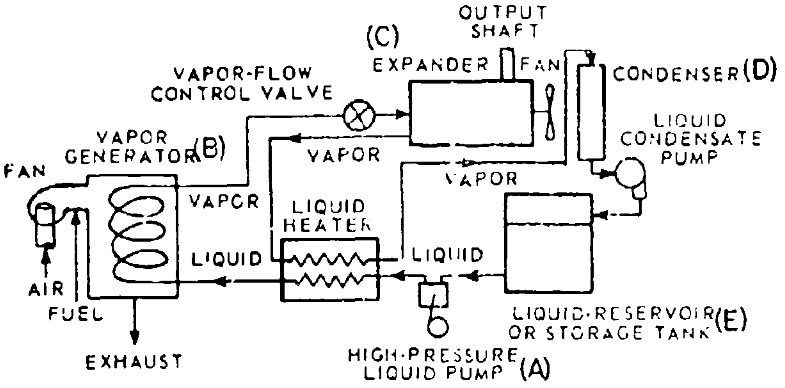

Figure 8-14. Schematic of Typical Rankine Cycle Steam Engine Components

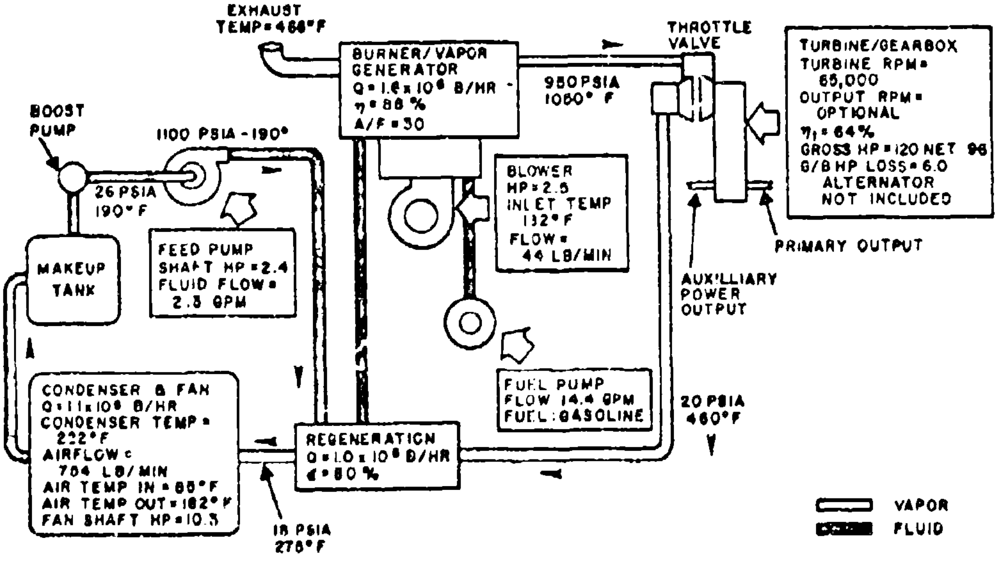

Figure 8-15. Lear Vapor Turbine System Design Point Thermodynamic Cycle BSFC = .91 Rankine Cycle Eff. = 14%

TABLE 8-5
TECHNICAL DATA OF RANKINE CYCLE SYSTEMS*

	TECO	SES	AEROJET	LEAR
Working Fluid	Fluorinol 85	Water	AEF 78	Water
Gross Horsepower	147	145	135	120
Net Horsepower	131	131	745	96
Shaft RPM	1800	1500	26500	65000
Inlet Temperature (°F)	550	1000	550	1050
Inlet Pressure (psia)	700	1000	1000	950
Overall Efficiency (%)	12	16	10	16
Weight (pounds)	1213	1400	1400	800

*This data was extracted from the Environmental Protection Agency's third summary report of the Automotive Power Systems Contractors Coordination Meeting, 20-21 June 1972.

Typically, the Lear vapor turbine system is a compact unit with the combustor being an integral part of the vapor turbine assembly. Combustion occurs under fuel rich conditions to retard the formation of oxides of nitrogen. The addition of air completes the combustion of hydrocarbons. The tube bundle, or convection bank, is a counterflow heat exchanger. This means that the feed water from the regenerators is injected at the outermost coil in the radial group and the superheated steam is extracted at the end of the innermost coil. Thus the hottest combustion gases heat the hottest fluid. This vapor generator assembly is efficient and compact enough for acceptable installation in existing vehicular engine compartments.

8.3.3.3.3 Working Fluid Studies. Many studies have been conducted by different manufacturers into what working fluids should be used in their systems. The initial efforts related to fluids were devoted to defining fluid selection criteria for both the turbine and reciprocating expanders, and the development of non-ideal mixture analysis techniques for predicting the thermodynamic properties of these mixtures.[1]

Several hundred single compounds and mixtures have been screened for thermal stability in sealed capsules at the required operating temperatures. The current result of these tests and the evaluations in terms of other desired criteria has yielded two classes of fluids as candidates showing the best potential for the intended application. They are the fluorinated aromatics and water solutions of pyridine.

The fluorinated aromatics are very expensive but are also stable at the working temperatures and are considered non-flammable. Manufacturing costs studies have been conducted for these fluids. Assuming a large production volume, the results indicate that costs could be substantially reduced.

The water solutions of pyridine and methyl pyridine are inexpensive but their acceptability in terms of flammability and toxicity have yet to be evaluated. From a thermodynamic standpoint, these fluids may be suitable for both turbine and reciprocating engines by varying the concentration of the amine.

8.3.3.4 Advantages and Disadvantages. As with any power unit, both advantages and disadvantages exist. One of the most interesting characteristics of the Rankine cycle systems is that their overall fuel economy improves under partial load conditions, since the heat exchangers, such as the boiler, condenser, and other heat recovery exchangers, improve in efficiency under partial loads. Due to this improved efficiency, the emissions are also lower. Combining these facts with other advantages, such as its multi-fuel capabilities, low noise and vibration levels, and high reliability, it can be concluded that the Rankine-cycle engine is a feasible GSE prime mover candidate.

The major disadvantage of the Rankine-cycle system is its early state of development. Although much work has been done on each of the various components, their collective design remains to be optimized. The physical size of the combustor and the condenser must be further reduced before general automotive use of the engine becomes practical.

8.3.4 Stirling Cycle Engines.

8.3.4.1 Principles. The Stirling engine is a hot gas, external combustion engine, which compresses a quantity of gas at low temperature and expands it at a high temperature. Theoretically, the Stirling engine has the same ideal efficiency as the Carnot cycle, operating between the maximum and minimum gas temperature. The cycle consists of the following four processes (Figure 8-16):

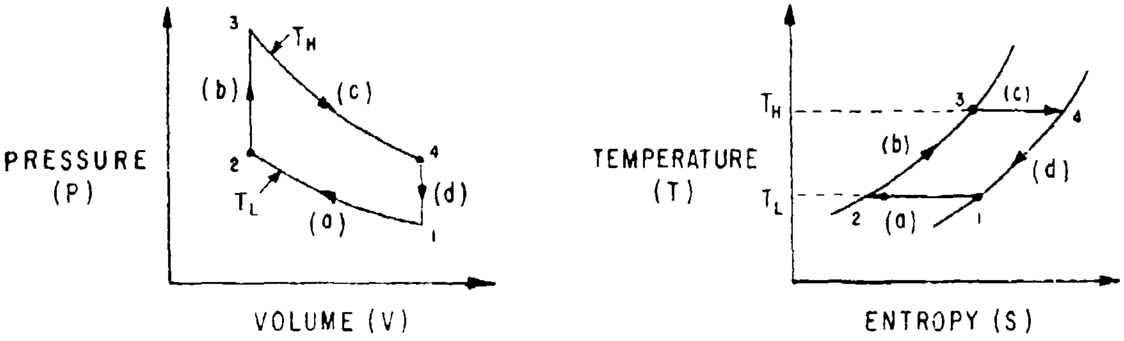

Figure 8-16. The Stirling Cycle

a) Constant temperature compression, in which heat is rejected.

b) Constant volume addition of heat which was stored in the regenerator from the preceding cycle.

c) Constant temperature addition of heat as the piston moves from minimum to maximum displacement.

d) Constant volume storage of heat, as the working fluid returns to the initial low temperature condition.

The gas temperature is periodically changed by causing a displacer piston to transfer the gas back and forth between two spaces, one at a fixed high temperature, and the other at a lower fixed temperature (Figure 8-17). When the displacer is raised, the gas flows from the hot space via the heater and cooler ducts into the cold space. When the displacer moves downwards, the gas returns to the hot space along the same path. During the first transfer stroke, the gas has to yield a large quantity of heat to the cooler while an equal quantity of heat has to be taken up during the second stroke from the heater. A regenerator is inserted in the duct between the hot and cooler sections to prevent the unnecessary loss of this heat. This regenerator consists of a space filled with a compact, high density, porous material to which the hot gas yields heat before entering the cooler and absorbs this stored heat prior to its entry into the hot section.[22]

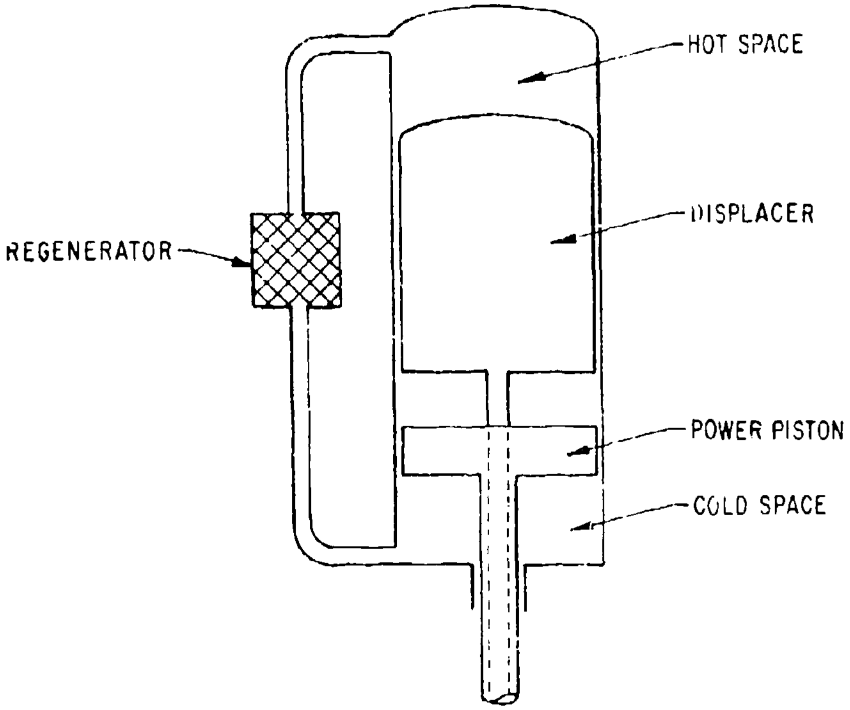

Figure 8-17. Stirling Engine Schematic

The displacer system, which serves to move the gas through the heating and cooling elements, is combined with a power piston, which compresses the gas while in the cold space and allows it to expand while in the hot space. Because of the temperature differences, less energy is consumed in compression than during expansion and a surplus of energy results. This excess energy is converted to useful work through a drive mechanism.

8.3.4.2 Development. In 1816, Reverend Robert Stirling invented what is now called the Stirling engine and in 1827, built the first successful version. The engine showed little future until Philips Research Laboratories of Netherlands started an intensive development program in 1938. In the 1950's, General Motors (GM) entered into an agreement with Philips to further develop the engine. The many improvements that resulted made the use of the engine much more feasible for a wide range of applications. In 1957, an engine was developed by GM for NASA to be used on a space satellite. Work continued at GM on variations of the Stirling engine until 1970, when their agreement with Philips was terminated. At this point, the Ford Motor Company obtained a license to work with Philips to continue the development of the engine.

8.3.4.3 Problem Areas. Until recently, the Stirling engine did not appear to be a practical powerplant. Many problems were overcome but a few still exist.

8.3.4.3.1 Drive Mechanism. There are various ways to make the displacer and piston perform the desired movements. Most are complicated and their reliability is lowered considerably. Two different approaches have shown acceptable results. In the first system, know as a "Rhombic Drive" (Figure 8-18),[18] each cylinder must have its own drive unit and its own combustor. The rhombic drive unit consists of twin cranks and connecting rod mechanisms offset from the central axis of the engine. The cranks rotate in opposite directions and are coupled by two gears. During its operation, the displacer shaft moves through the hollow piston shaft in a sequence which is determined by the timing gears.

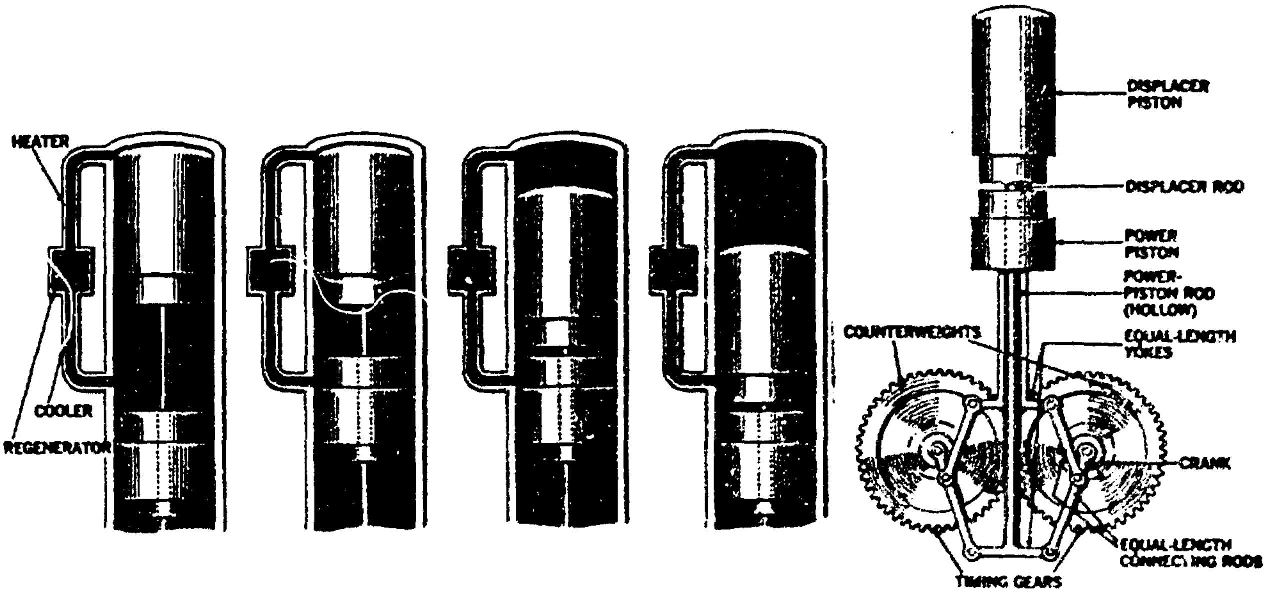

Figure 8-18. Rhombic Drive System

The rhombic drive version of the engine is extremely impractical for vehicular use due to the necessity of individual combustors. However, the swashplate drive system made vehicular use of the Stirling engine practical because of its decreased weight and complexity. In the swashplate system, which does not use a displacer piston nor a separate combustor for each cylinder (Figure 8-19),[18] the piston rods exert pressure against an angled plate, transmitting a wedging action and causing the swashplate to revolve, thereby rotating the output shaft. Four pistons, phased 90° apart, deliver one power impulse for every quarter turn of the output shaft. The swashplate system is now the accepted drive mechanism because of its smaller size, lower weight, and decreased complexity.[22]

8.3.4.3.2 Working Fluid. The working fluid used in the Stirling engine has a significant effect on its power output and the efficiency. While any gas can be used, low fluid friction and high heat transfer properties are so critical that most common working fluids are eliminated. The original Stirling engine ran poorly since air was used as the working fluid. After a thorough fluid analysis, it was determined that hydrogen had the best combination of properties. However, hydrogen is a highly flammable gas which requires many precautionary measures. The flame speed in hydrogen-air mixtures is far greater than in gasoline-air mixtures. Much greater explosive forces would result if the hydrogen were to be ignited.[22]

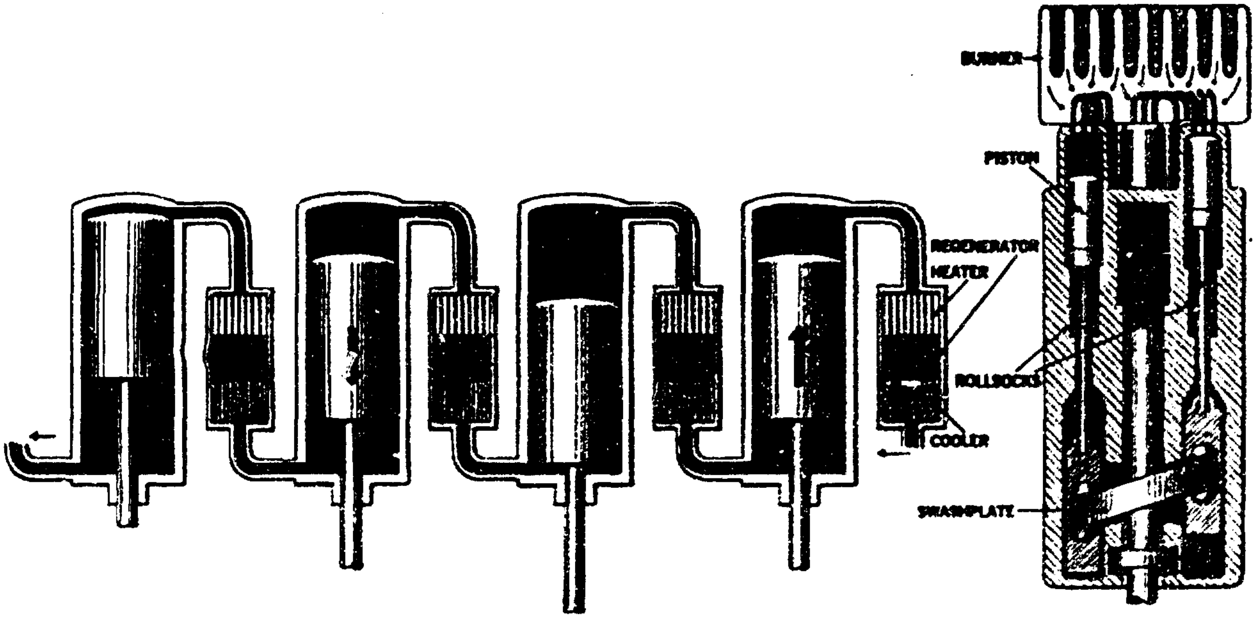

Figure 8-19. Swashplate Drive System

The search for methods that would reduce the hazards of using hydrogen is continuing. One method is to decrease the quantity of hydrogen needed by reducing the size of the manifolds, pumps, plumbing, and reserve bottles. It is expected that these efforts will ultimately make hydrogen acceptable for use in the Stirling engine.

8.3.4.4 Advantages and Disadvantages. The most significant advantages in the Stirling engine include both a multi-fuel capability and an improved fuel economy. Other advantages include a noise level about 20-40 dBA below diesel engines, an almost total lack of vibration, and a similar lack of pollution. Its reliability is extremely high and because oil changes are not necessary, maintenance is also reduced. The major disadvantage to using the Stirling engine is the hazard created by the use of hydrogen as the working fluid.

8.3.5 Stratified Charge Engines.

8.3.5.1 Principles. The stratified charge engine (Figure 8-20) is an unthrottled, spark ignition engine, which uses fuel injection to achieve selective stratification of the air-fuel ratio in the combustion chamber.[7] The engine develops a rich fuel mixture in the zone of the spark plug and a lean fuel mixture throughout the rest of the cylinder. Because a full charge of air is taken into the cylinder on each stroke, the need for inlet air throttling is eliminated. Under partial load conditions, all levels of stratification combined use an overall lean air-fuel mixture, resulting in increased fuel economy and reduced emissions.

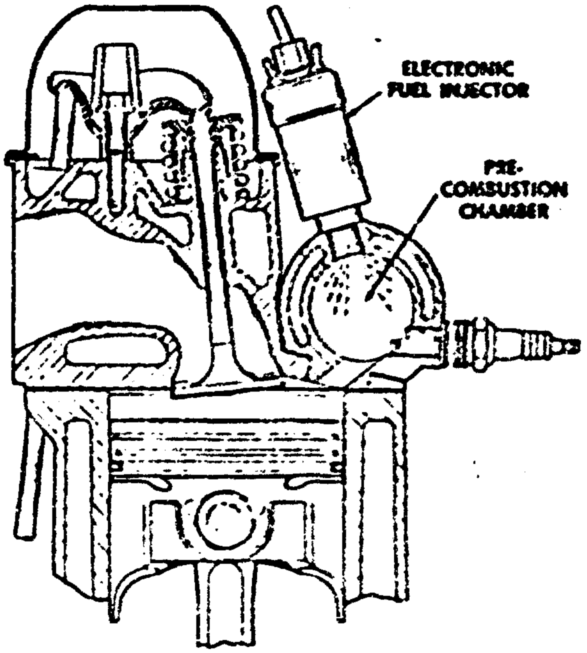

Figure 8-20. Prechamber Stratified-Charge Engine

The power output of the stratified charge engine is controlled by increasing or decreasing the amount of fuel injected into the combustion chamber. As the power demand increases, the fuel introduced into the cylinder also increases.

8.3.5.2 Development. Experiments have been conducted with stratified charge concepts since their inception in 1915 when they were used on diesel engines. Presently, these concepts are being used almost entirely to develop engines that will comply with the future emission standards set forth by the EPA.

Three different pollutants are regulated by the EPA: hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x). HC emissions are formed in an engine because the air-fuel mixture near the cylinder walls is too cool to burn. The unburned gasoline vapor that remains forms layers of hydrocarbons on the walls and is blown out during the exhaust stroke. CO emissions result when the fuel is not burned completely. This usually occurs when the mixture in the cylinder is fuel-rich during both the expansion and exhaust strokes. The NO_x are formed when nitrogen and oxygen combine at high temperatures early in the expansion stroke. With higher temperatures or more oxygen available in the cylinder, more NO_x emissions are formed.[19]

The purpose of the stratified charge concepts is to control the air/fuel mixture so as to control the emissions and increase fuel economy. A short discussion of the several different versions that have been developed follows.

8.3.5.2.1 Compound Vortex Controlled Combustion (CVCC). The CVCC engine was first developed by the Honda Motor Company in 1967. This system uses two carburetors, one of which is set to produce a rich mixture while the other gives a lean mixture. These carburetors provide for three layers of mixture, rich in the precombustion chamber, lean in the cylinder, and half-and-half in the connecting passage (Figure 8-21).

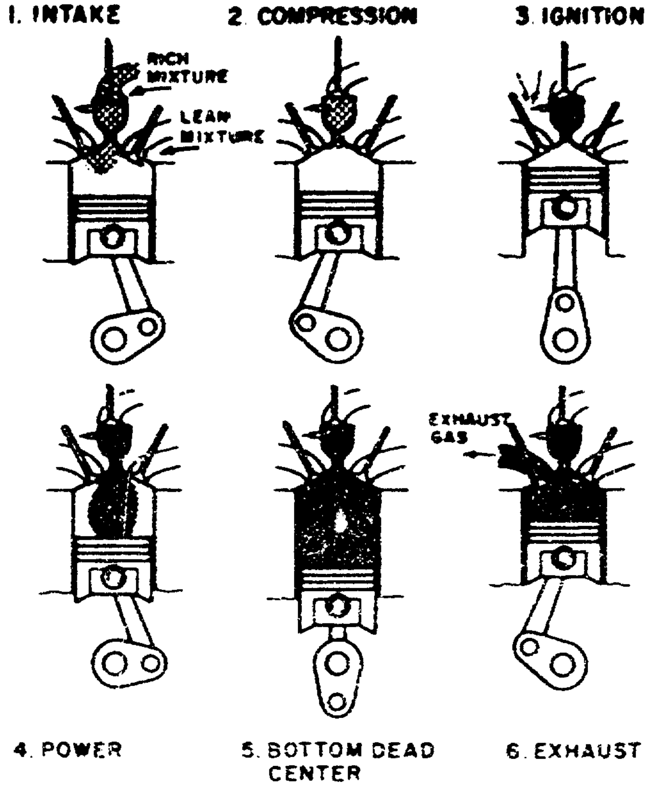

Figure 8-21. CVCC Engine Cycle

The fuel rich mixture is ignited and burns quickly and completely to keep CO emissions low while the flame front travels to the cylinder through the medium-rich mixture. The lean mixture in the cylinder burns more slowly and at a high enough temperature to assure complete combustion and low HC emissions but at a lower temperature than is needed for NO_x to form.[19]

Honda is continuing to develop the engine to further improve fuel economy and performance. Presently, this CVCC engine is one of the three engines certified as meeting the emission standards for 1975 set by the EPA.

8.3.5.2.2 Texaco Controlled-Combustion System (TCCS). The TCCS engine has been under development at Texaco since 1956. This system uses a combination of an air swirl, fuel injection, and positive ignition to reduce pollutant emissions. The creation of an air swirl in the combustion chamber is the basic principal for the operation of the system, with the rate of swirl directly influencing the combustion duration and the efficiency of the engine. Initial engine designs did not create an efficient air swirl, but with the use of a "cup-in-piston" combustion chamber configuration (Figure 8-22), an adequate swirl rate during combustion can be achieved.[15]

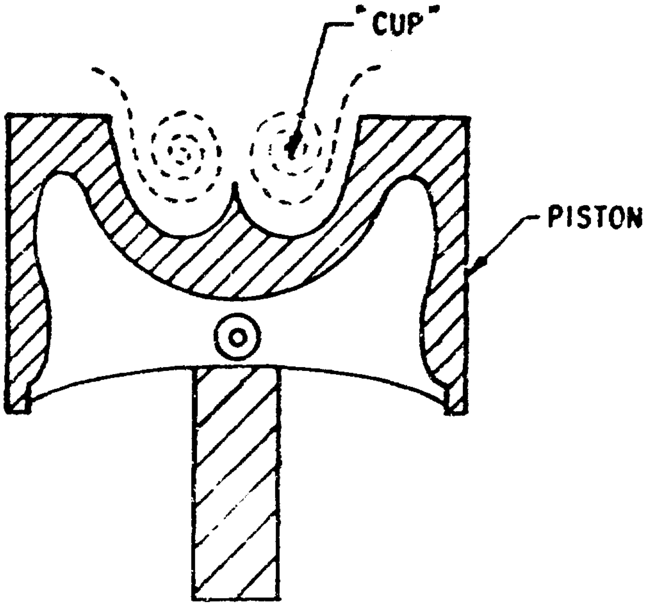

Figure 8-22. Cup-in-Piston Design

In 1963, the United States Army Tank-Automotive Command (USATACOM) signed a contract with Texaco to apply the TCCS concept to a military engine. As a result, fuel consumption was reduced by 30% over the standard military gasoline engine. The new engine also has a multi-fuel capability which allows it to use gasoline, JP, or diesel fuel. Work is continuing to make additional improvements.

8.3.5.2.3 Stratified Charge Rotating Combustion Engine. In 1962, various types of stratified charge configurations were evaluated by Curtiss-Wright on a rotating combustion engine (see section 8.3.1). The system, developed by Curtiss-Wright, uses JP-4 or 5 fuel which is directly injected into the combustion chamber by high-pressure diesel-type nozzles (Figure 8-23) located adjacent to the spark plug and operated in synchronization with the ignition timing. The burning takes place as the fuel is injected and has an almost stationary flame front. Using this system, a low octane fuel would produce acceptable performance with low emission levels.[11]

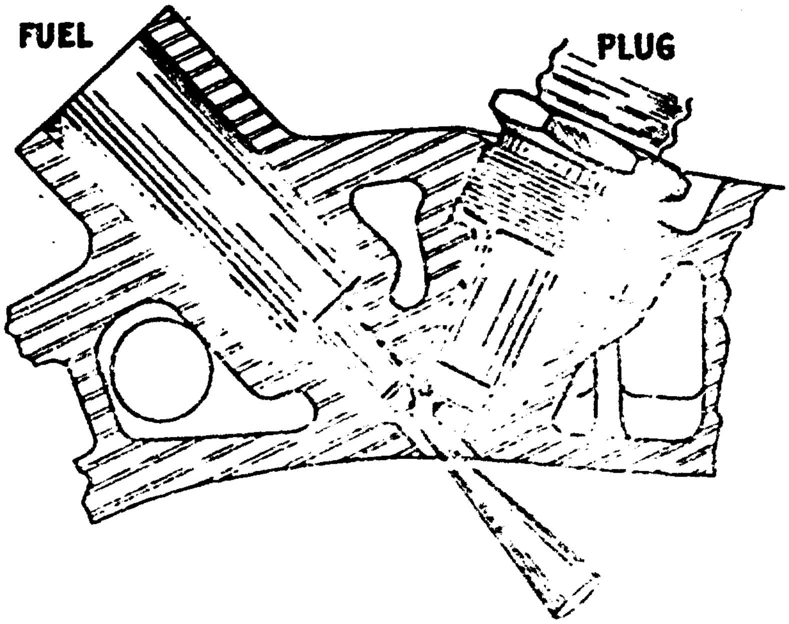

Figure 8-23. Fuel Injection in a Stratified Charge RC Engine

Development is continuing on this Curtiss-Wright version to improve the fuel economy which is still below expectations. Most of the development involving this type of stratified charge engine was accomplished under contracts let by the Navy.

8.3.5.3 Problem Areas. Since most of the stratified charge engines were developed primarily to meet emission standards set by the EPA, other inherent problems with the engine were neglected. Basically, a stratified charge engine is just a modified, automotive type, conventional piston engine with the same problems.

8.3.5.3.1 Performance. Because of the overall lean air fuel mixture used in the combustion process, a 20% loss in power can be expected when compared to a normally carbureted engine. This loss of power severely affects the performance of the engine, especially during high power demand periods. Work to correct this problem is continuing by changing the fuel injector location and the injection duration. Significant improvements in performance were observed with these changes, but the emission levels also increased.

8.3.5.3.2 Complexity. A significant problem with conventional piston engines has been their complex mechanical systems (such as the valve train, ignition system, etc.). Since the stratified charge engine is just a modification of this engine, the same complexity still exists but with the additional, complex, stratification mechanism. This mechanism consists of a fuel injection nozzle and a fuel metering device which needs constant servicing to keep it operating correctly. These fuel injection systems must be very precise and require very carefully tuned fuel metering and control elements.

8.3.5.3.3 Advantages and Disadvantages. Improved fuel economy and low emissions are the most often mentioned advantages of the stratified charge engines. Its ability to use either low octane or JP fuels is also a favorable feature. However, many disadvantages exist. Being a modification of the conventional piston engine, the engine is significantly increased in size, weight, and cost. Also, with the increased complexity of the fuel system, reliability is decreased. As a result of the precise fuel injection requirement, there exists a need for additional and more frequent maintenance.

8.3.6 Electric Drive Systems.

8.3.6.1 Principles. An electric drive system usually includes a power source (such as batteries or fuel cells) which feeds electrical energy to a conversion device (such as an electric motor). Electric motors usually convert electrical power from the source to useful mechanical torque at high conversion efficiencies. They usually produce maximum torque at stall, and can be electrically reversed to change the direction of travel.

8.3.6.2 Development. As the result of many years of research, electric motors have become some of the most highly developed energy conversion devices in existence. However, research is still continuing to improve the power source characteristics. Batteries need redesigning to give quicker recharging times, reduced weight and volume, and increased life span. Fuel cells need more development to improve their effectiveness and reduce their high procurement and operation costs.

8.3.6.3 Problem Areas. The problems associated with mobile electric drive systems are basically those associated with the power source. Batteries and fuel cells are the only currently feasible power sources and each has its own peculiar problems.

8.3.6.3.1 Batteries. The major problem with battery systems involves having sufficient power available when it is needed. Batteries are not always immediately ready for service because they must be recharged frequently. The currently, high amperage mobile power applications can only be filled by chemical storage batteries. These have long recharging periods, are expensive, and have limited duty cycle life spans. To produce the amount of power really required for vehicular applications, present batteries are too heavy, too costly, and take up too much space. Research is being conducted to develop new types of batteries with both reduced weight and volume.

8.3.6.3.2 **Fuel Cells.** Fuel cells are reaction cells which electrochemically combine oxygen and hydrogen to produce electricity and water. These systems are very reliable but extremely costly. One problem associated with fuel cells involves the hazards of using hydrogen as a fuel because of its high volatility. Reformers can be used to convert some present fuels into usable hydrogen, but these add weight, bulk, and complexity to an already complex system. They also reduce the total efficiency of the system since the conversion process itself consumes some electrical energy.

8.3.6.4 **Advantages and Disadvantages.** Electric drive systems are quiet, dependable, and non-polluting. They have very few components which require maintenance and most of the wearing parts, such as contacts and bearings, are easily replaceable. Complex transmissions are not required since the motors are electrically reversible and variable in speed.

The disadvantages of the electric drive systems, as previously indicated, mainly involve the power source limitations. Other disadvantages include the generally high cost of the entire system and the poor reliability and complexity of the system voltage controllers.

8.3.7 Flywheels.

8.3.7.1 **Principles.** The flywheel is a device which can store kinetic energy for later use in propelling a vehicle. The flywheel is a disk, usually made from steel, which is rotated to a high speed by some device, and then left to rotate freely. The high speed spinning disk is then permitted to dissipate energy to a drive system. This propulsion system is usually a hydrostatic or electric drive.[21]

8.3.7.2 **Development.** During the past few years, there has been a renewal of interest in flywheel concepts. Both General Dynamics and North American Aviation have explored the possibility of using flywheel-powered devices. General Dynamics is currently investigating a system using a glass-fiber wheel with an electric drive system. The results have been favorable and additional development is continuing.

8.3.7.3 **Problem Areas.** The major problem in the flywheel system involves the transference of the stored energy in the flywheel to the wheels of the vehicle. A continuously variable drive is required because the flywheel must decelerate smoothly. These systems are very complex and extremely expensive. Much more research is needed before flywheel systems become feasible.

8.3.7.4 **Advantages and Disadvantages.** The advantages of the flywheel system are that it is pollution-free and that all the stored energy can be removed rapidly.

The disadvantages of these systems are numerous. They are quite bulky and very expensive. Drive systems are complex and a system is needed to "wind-up" the flywheel. Safety is a critical problem, for with the massive disk rotating at a very high speed, any failure of the disk or its supporting structures would be catastrophic.

8.4 Data Comparisons. Comparisons between these prime mover candidates are difficult because of each one's varying stage of development, especially with improvements being made constantly. Most of these prime movers have qualities which would immediately be more advantageous in GSE than the present prime movers. (Table 8-6).

8.4.1 Noise. Generally, the noise levels generated by all of the candidates, except the stratified charge engines, are lower than the engines currently used in GSE.

8.4.2 Fuel Requirements. At the present time, most of the new candidates have a multi-fuel capability while the Wankel engine can only burn gasoline. The electric drive and flywheel systems are not fuel powered at this time.

8.4.3 Fuel Economy. The Stirling engine is the only prime mover candidate expected to produce a significant improvement in fuel economy. Researchers working on the other candidates predict that with additional development, their fuel economy can be improved as well.

8.4.4 Emissions. The low emission levels generated by these candidates is one of the prime reasons why engine manufacturers are continuing developmental work on new engines. The emissions are lower than those generated by the existing prime movers.

8.4.5 Reliability. Reliability is again difficult to compare because of the various stages of development. The Wankel engine, the only one in mass production, has demonstrated an acceptable level of reliability. It is expected that all of the new prime movers will be more reliable than the engines currently in use.

8.4.6 Dimensions. These new prime movers are about the same size or smaller than the presently used engines. The stratified charge engine may be larger, but further development should reduce this size. The Wankel engine is the smallest, being about half the size of a conventional gasoline engine.

8.4.7 Vibration. All the new prime movers, except for most of the stratified charge engines, are almost vibration free. The stratified charge rotary engine is almost vibration free because of its lack of reciprocating motion.

8.4.8 Safety. Safety problems could possibly create drawbacks for several of the candidates. The Stirling engine using hydrogen as a working fluid creates fire and explosion hazards. Sudden release of the high pressures used in the Rankine cycle engines could be catastrophic. The fuel cells and battery systems give off explosive hydrogen gas through chemical reactions. However, all of these safety problems could be solved with further development.

TABLE 8-6

COMPARISON OF EXISTING AND NEW PRIME MOVERS

	Conventional Gasoline Engine	Diesel Engine	Rotary Engine	Rankine Cycle		Stirling Engine	Stratified Charge	Fuel Turbine	Fuel Cells	Battery	Flywheel
				Reciprocating	Turbine						
Reliability	0	+1	-1	+1	+2	+2	-1	+2	+1	-2	-2
Maintainability	0	+1	+1	+2	+2	+2	-1	+2	-1	-2	-2
Dimensions	+1	0	+2	+1	+1	+1	+1	+1	-1	-1	-1
Weight	+1	0	+2	+1	+1	+1	+1	+1	-1	-1	-1
Economy (Fuel)	0	+1	-1	-1	-1	+2	-1	-1	-1	-1	-1
Fuel Requirements	0	+1	-1	+2	+2	+2	+2	+2	-2	N/A	N/A
Emissions	0	+1	+1	+2	+2	+2	+1	+1	+2	+2	+2
Vibration	+1	0	+2	+2	+2	+2	-1	+2	+2	+2	+1
Noise Level	+1	0	+1	+1	+1	+2	-1	+1	+2	+2	+1
Safety	0	+1	+1	+1	+1	-1	+1	+1	-1	-1	-1
Complexity	+1	0	+2	+1	+2	+1	-1	+1	-2	+1	-1
Costs	+1	0	+1	+1	+1	+1	+1	-1	-1	-1	-1
Standardization	+1	0	+2	-1	-1	-1	+1	-1	+1	+1	-1

+2 Definite Advantage
+1 Slight Advantage

-1 Slight Disadvantage
-2 Definite Disadvantage

N/A – Not Applicable
0 – Standard

8.4.9 Maintainability. The need for scheduled maintenance is decreased with closed cycle systems such as the Stirling, Rankine cycle, and gas turbine engines. Also, oil changes and tune-ups are not required with these systems. The stratified charge and Wankel engines still required periodic servicing since they still use spark plug ignition systems.

8.4.10 Complexity. The number of parts used in most of the candidate prime movers is decreased. The Wankel incorporates both reduced complexity and about half as many parts as currently used gasoline engines, but the stratified charge engine has the added complexity of its fuel metering system. The Rankine cycle, Stirling, and gas turbine engines are basically simple, but all require very complex control systems.

9. FUTURE EFFORTS

The investigation into the development of the Wankel, Stirling, and gas turbine engines, and the Rankine cycle systems will continue. The installation and testing of a Wankel engine in a weapons loader will commence in the near future. Prototype Rankine cycle engines will be obtained to determine the feasibility of their use in GSE. The gas turbine and Stirling engines will also be evaluated in the GSE environment. At the conclusion of the evaluation of these candidates, on optimal replacement prime mover will be recommended.

10. REFERENCES

1. Bolt, J.A., and D.E. Cole. Low Emission Power Plant Systems; A Technical Evaluation. University of Michigan. 1972.

2. deBiasi, Victor. "2500 Degree F. Target for Vehicular Ceramic Turbine". Gas Turbine World. 2 (Oct-Nov, 1972) pp 12-19.

3. Environmental Protection Agency. Summary Report - Automotive Power Systems Contractor's Coordinator Meeting. June, 1972.

4. Estes, E.M.. "Alternate Power Plants for Automotove Purposes." Proceedings of the Institute of Mechanical Engineers, 186 (1972), pp 125-140.

5. Flynn, Jr., G., W.H. Percival and F.E. Heffner. "GMR Stirling Thermal Engine, Part of the Stirling Engine Story - 1960 Chapter." SAE Transactions, 68 (1960), pp 665-683.

6. Ford Motor Co.. New Turbine Power by Ford. Sales Brochure on Ford 3600 Series Turbine. Dearborn, Michigan.

7. General Motors Corporation. 1972 Report on Progress in Areas of Public Concern, February 10, 1972.

8. Jones, C. "The Curtiss-Wright Rotating Combustion Engines Today." SAE Transactions, 73 (1965).

9. Jones, C. "New Rotating Combustion Powerplant Development." SAE Transactions, 74 (1966).

10. Jones, C. "A Survey of Curtiss-Wright's 1958-1971 Rotating Combustion Engine Technological Developments." SAE Paper 720468, 1972.

11. Jones, C., and H. Lamping. "Curtiss-Wrights Status of the Stratified Charge Rotating Combustion Engine." SAE Paper 710582.

12. Lear Motors Corporation. Water Base Rankine Vapor Turbine System. EPA Contract 68-01-0462. 1973.

13. Ludvigsen, Karl. "Stirling Engine." Road and Track, 24 (March 1973), pp 88-91.

14. Maki, E.R. and A.O. DeHart. "A New Look at Swash-Plate Drive Mechanisms." SAE Paper 710829, 1971.

15. Mitchell, E., Alperstein, M. and Faist, C.H. "A Stratified Charge Multifuel Military Engine." SAE Paper 720051, 1970.

16. Mobile Technical Bulletin. "Rotary Engines-Wankel." Mobile Oil Corporation. New York, 1971.

17. Norbye, Jan P. The Wankel Engine. Chilton Book Co. Philadelphia, 1971.

18. Norbye, Jan, and Dunne, Jim. "Ford Gamble: Stirling Cycle Engine Promises Low Emissions Without Add-ons." Popular Science, 202 (February, 1973), pp 72-76.

19. Norbye, Jan P., and Jim Dunne, "Honda's New CVCC Car Engine Meets 1975 Emission Standards Now." Popular Science, 202 (April, 1973), pp 79-81.

20. U.S. Dept. of Health, Education and Welfare. "Control Techniques for Carbon Monoxide, Nitrogen Oxide and Hydrocarbon Emissions from Mobile Sources." NAPCA Publication No. AP-66, 1970.

21. U.S. Dept. of Health, Education and Welfare. "Study of Unconventional Thermal, Mechanical and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles." NAPCA Publication No. APTD 69-51, October, 1969.

22. Welsh, H.W., et. al., "The Study of Low Emission Vehicle Power Plants Using Gaseous Working Fluids." Thermal Mechanical Systems Co., Report No. SR-20 under contract EHSH-71-003, August, 1972.

23. Wright, Edward S. "Auto Pollution Solution: The Gas Turbine?," Mechanical Engineering, 93 (June, 1971) pp 25-27.

APPENDIX A

ACTIVITIES AND PERSONNEL VISITED

ACTIVITY	PERSONNEL
NAS NORFOLK	W. Standbridge P. Buckman
NAS OCEANA	J. F. Barrere B. J. Eaton CWO Amos
LEAR MOTORS CORPORATION Reno, Nevada	Peter Lewis Joseph Walsh
WILLIAMS ENGINE COMPANY Ambler, Pennsylvania	Thomas V. Williams G. Lupton Broomell
CURTISS WRIGHT CORPORATION Woodridge, New Jersey	Vincent D. Pohlmeyer
THERMO ELECTRON CORPORATION Waltham, Massachusettes	Jerry Davis Dr. Peter Teagen
CHRYSLER CORPORATION Detroit, Michigan	James P. Franceschina
FORD MOTOR COMPANY Dearborn, Michigan	Benjamin T. Howes Norman Postma
GENERAL MOTORS CORPORATION Warren, Michigan	Worth Percival F. Earl Heffner
ENVIRONMENTAL PROTECTION AGENCY Ann Arbor, Michigan	S. Kramer

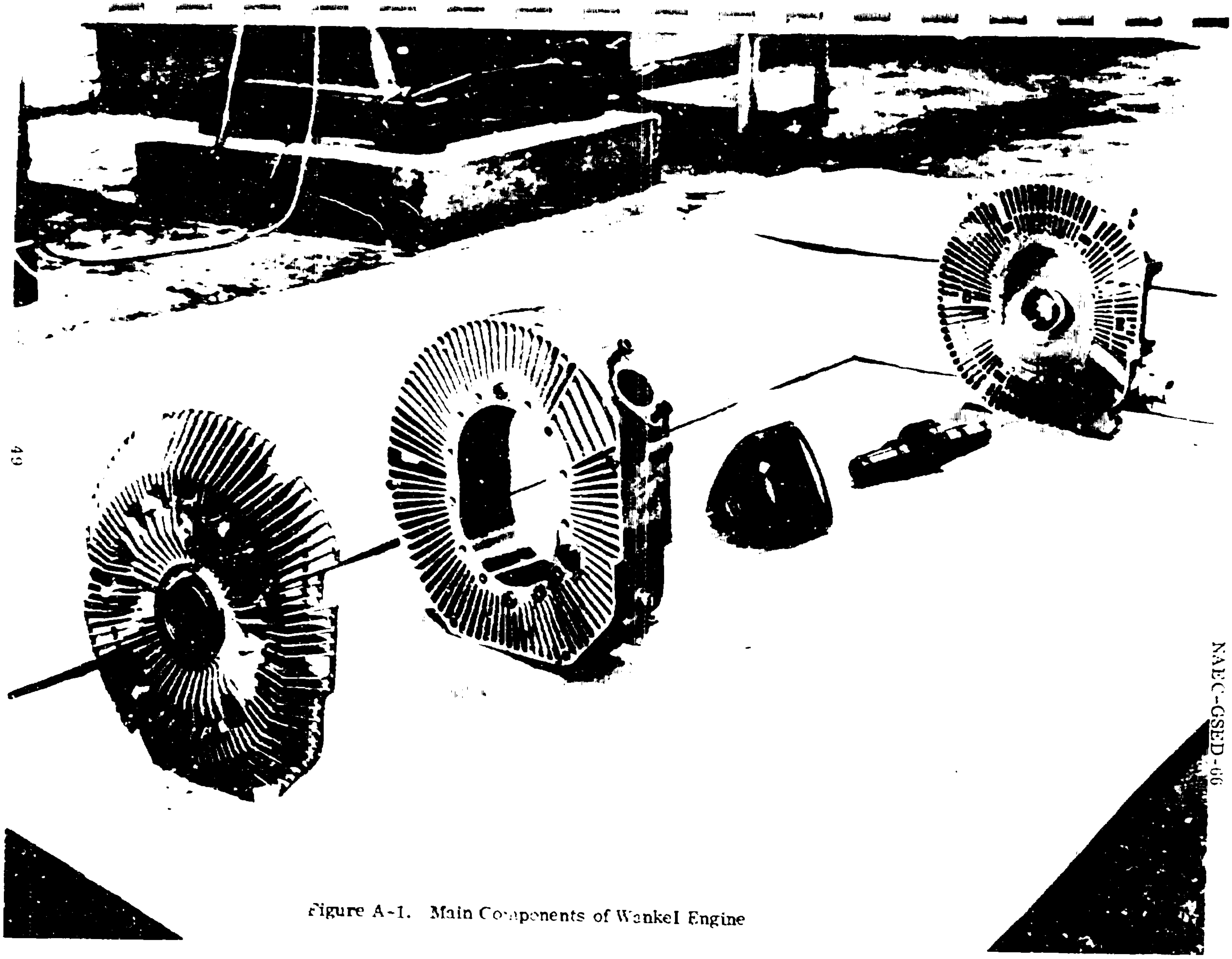

Figure A-1. Main Components of Wankel Engine

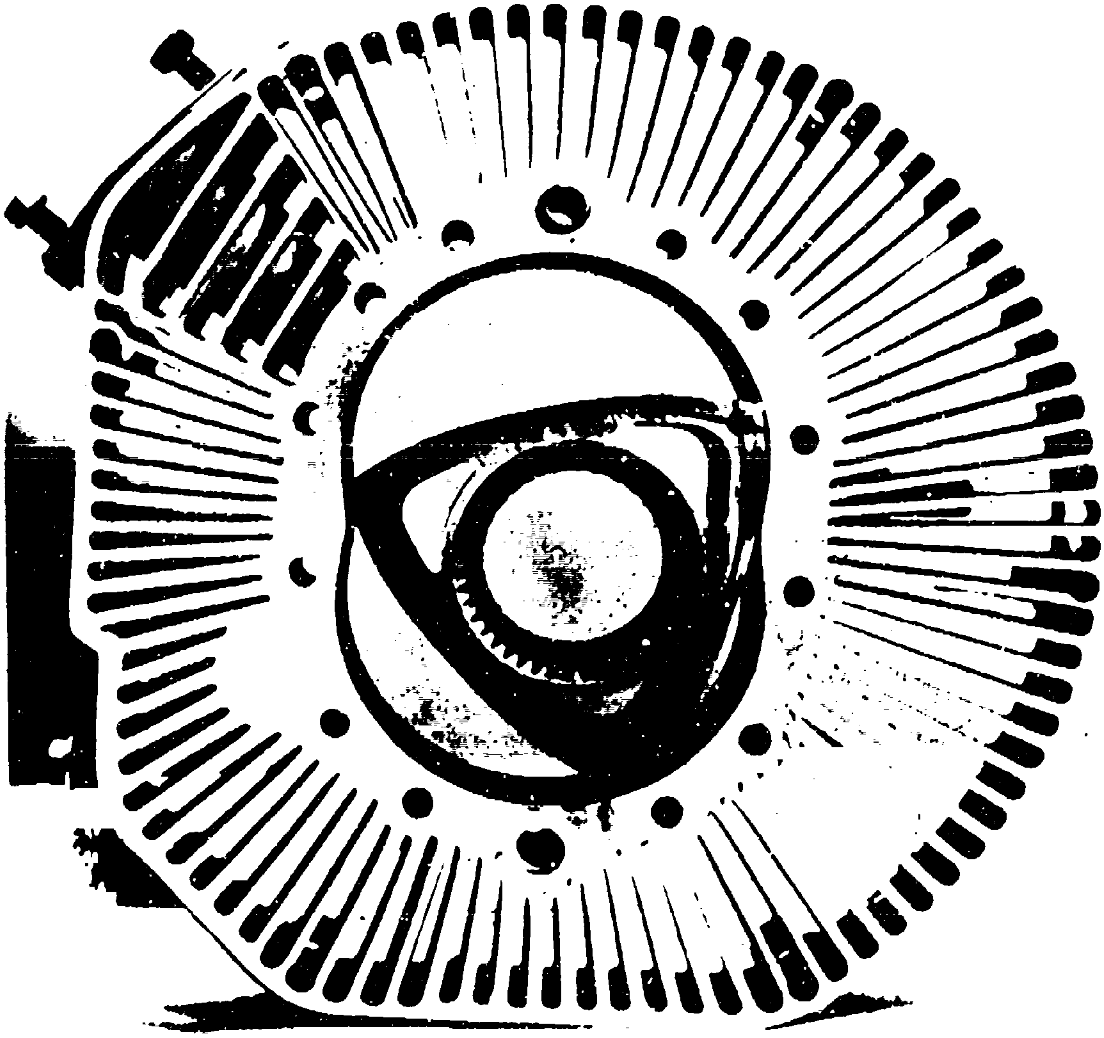

Figure A-2. Wankel Engine Rotor in Housing

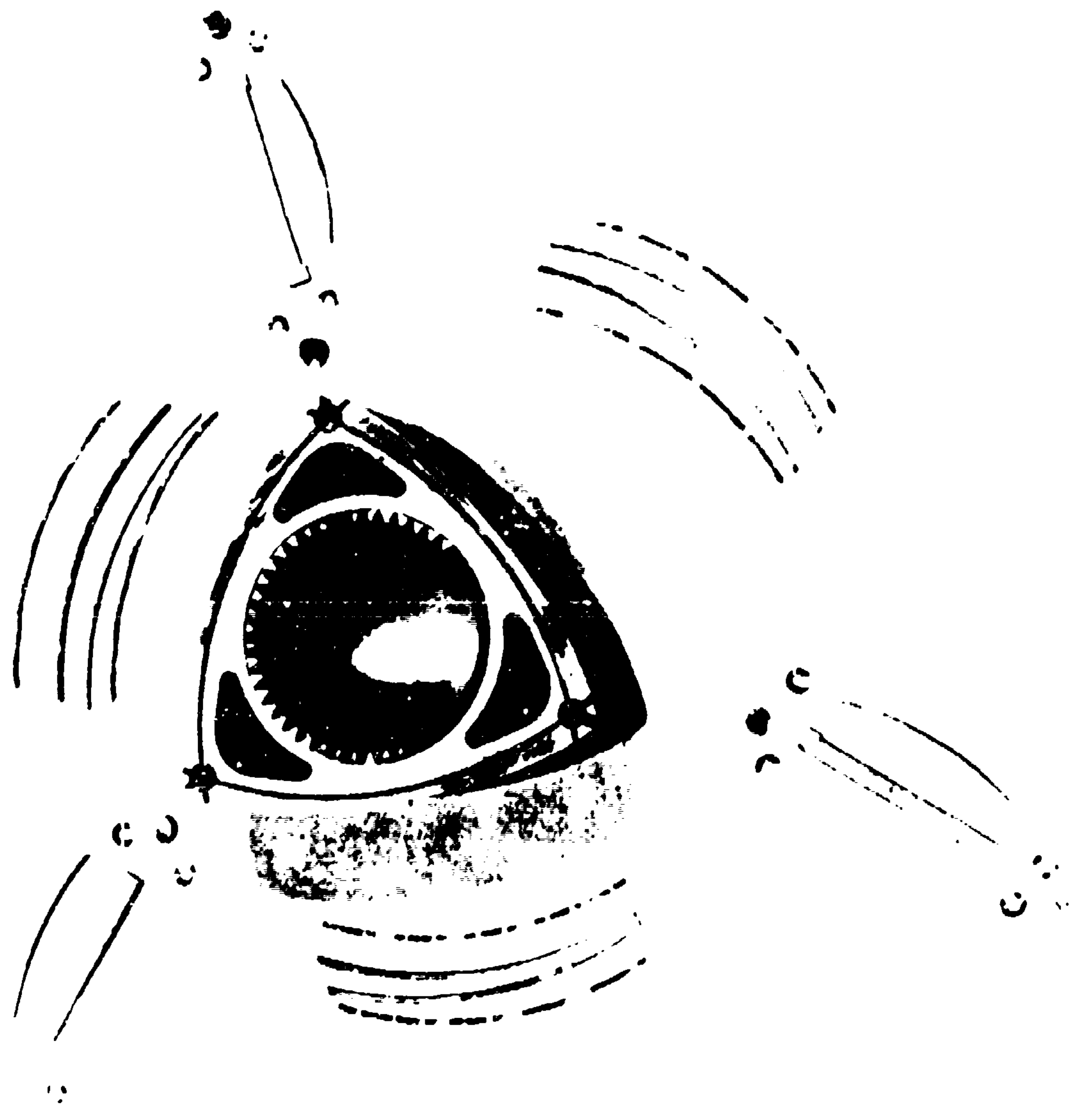

Figure A-3. Rotor Seal Arrangement in Wankel Engine

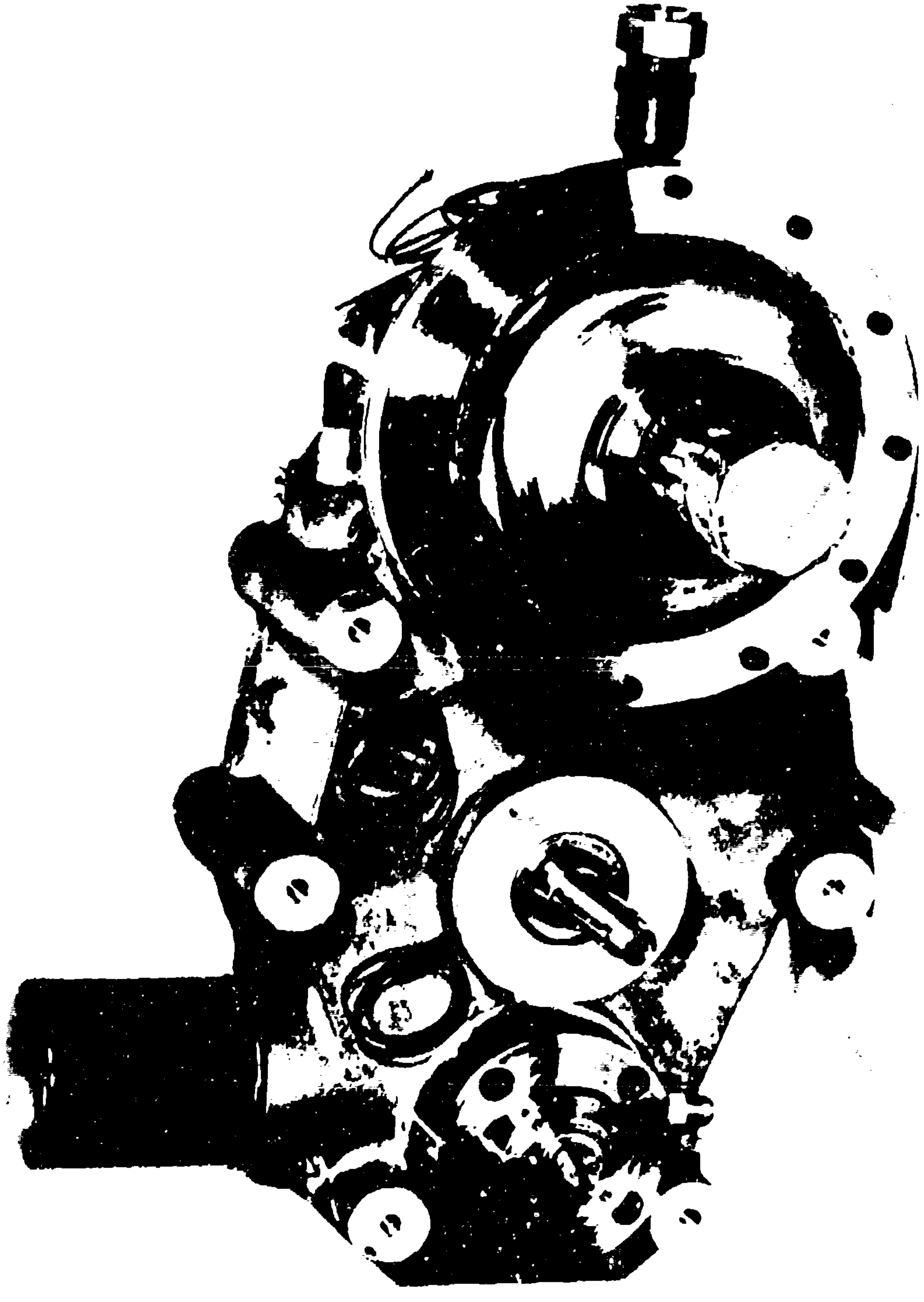

Figure A-4. Lear Organic Turbine and Gearbox