Cost Study for Phase Two Small Engine Emission Regulations

Draft Final Report

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1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has determined that nonroad equipment and engines contribute significantly to emissions and air pollution. A particular focus is on small spark-ignition (SI) engines that power equipment such as lawnmowers, hedge trimmers, generator sets, and small pumps. In an effort to reduce these emissions, EPA is taking steps to phase-in emission reduction regulations on small SI engines. The California Air Resources Board is also pursuing a phased-in approach for reducing emissions from utility engines.

1.1 Phase 1 Emission Standards

EPA published Phase 1 emission reduction regulations for small spark-ignition (SI) engines on July 3, 1995. These regulations contain exhaust emission standards for new small SI engines at or below 19 kilowatts (25 horsepower) in five classes (Table 1). The small SI engine are divided into five classes corresponding to handheld equipment engines and non-handheld equipment engines.

Table 1: Phase 1 Emission Regulations for Small Spark-Ignition Engines.

Engine Class	Displacement (cc)	Equipment Type	HC+NOx (g/kw-hr)	HC (g/kw-hr)	CO (g/kw-hr)	NOx (g/kw-hr)
I	<225	non-hand-held	16.1	--	469	--
II	≥225	non-hand-held	13.4	--	469	--
III	<20	handheld	--	295	805	5.36
IV	≥20 & <50	handheld	--	241	805	5.36
V	≥50	handheld	--	161	603	5.36

These standards must be met by new engines by model year 1997. In-use deterioration is not considered in Phase 1. In the rulemaking, EPA evaluated the cost implications of the emission levels on industry (EPA, May 1995). The EPA Phase 1 standards are similar to the emission reduction (Tier 1) standards set by the California Air Resources Board (CARB).

1.2 Phase 2 Emission Standards

From 1993 to February 1996, EPA participated in a regulatory negotiation process involving government, industry, and environmental groups to develop Phase 2 emission regulations for small SI engines. In subsequent efforts, a Statement of Principles (SOP) was developed on handheld engines. This SOP proposes Phase 2 deteriorated certification standards for handheld engine, to be met at the useful life hours (Table 2).

Table 2: Statement of Principles (May, 1996) on Phase 2 Emissions Levels for Class III, IV, and V Engines (Handheld Equipment).

Engine Class	HC + NOx (g/kW-hr)	CO (g/kW-hr)	Useful Life (Hours) Consumer/Commercial
III	210	805	50/300
IV	172	805	50/300
V	116	603	50/300

These levels for Class III, IV, and V engines will be proposed as straight, rather than averaging standards; thus, each engine produced would have to meet these levels. EPA will propose that these levels be phased in over four years beginning with model year 2002, as follows:

Model Year	Percent of Production
2002	20%
2003	40%
2004	70%
2005	100%

An SOP is being developed for the non-handheld engines.

1.3 Scope and Approach of Cost Study

The purpose of this cost study is to provide further cost-benefit analysis for the rulemaking(s) for Phase 2 standards for small ($\leq$ 19 kilowatts) spark-ignition engines used in handheld and non-handheld equipment. The effort was to determine the incremental costs incurred by manufacturers over the Phase 1 baseline costs to reduce emissions further to meet Phase 2 emission standards. In the study, data sources consulted included:

(1) Regulatory Impact Analysis and Regulatory Support Document for Emission Standards for New Nonroad Spark-ignition Engines at or Below 19 Kilowatts;
(2) regulatory negotiation task group reports;
(3) EPA alternative technology assessment reports;

(4) CARB technical review report;
(5) cost, emissions, technology, useful life, and deterioration factor (DF) information from a variety of engine manufacturers;
(6) engine data from the Power Systems Research ENGINDATA database;
(7) conversations with engine and equipment manufacturers, distributors, and retailers; and
(8) inhouse literature

Some sections of the study on handheld equipment engines were based on cost analyses performed for CARB in support of technology reviews of Tier II. It should be noted that some of the manufacturer information was classified as confidential business information, but was guaranteed by EPA and its contractors to not be used in this study.

The primary approach used in this study was to perform a bottom-up analysis to estimate the incremental costs for modifying or changing an engine to reduce emissions below Phase 1 levels. The scope includes engines used in both handheld and non-handheld equipment. The types of costs estimated include variable hardware costs (e.g., materials), production costs (e.g., tooling), and fixed costs (e.g., research and development). The bottom-up approach builds up the cost estimate based on the hardware, production, and fixed costs associated with individual engine parts that will be needed or modified. In some cases, the actual engines were purchased and taken apart to determine the need for additional or modified parts. The cost estimates were based without reference to similar estimates developed by engine manufacturers.

The bottom up cost approach focused on six engine technology modifications identified by EPA as the most likely technologies that will be used by engine manufacturers to reduce emissions from Phase 1 standards (Table 3). The three technology modifications that apply to non-handheld equipment (engine classes I and II) are improved side-valve (SV) design, conversion to overhead-valve (OHV) design, and improved overhead-valve design. The three technologies that apply to handheld equipment (engine classes III, IV, and V) are improved two-stroke design, conversion of two-stroke to four-stroke design, and a two-stroke design with a catalyst.

Table 3: Engine Modification Technologies Addressed in Study.

Engine Class	**Equipment**	**Engine Modification Technologies Addressed in Study**
Class I and II	Non-Handheld	Improved Side-valve Design Improved Overhead-valve Design Conversion of Side-valve to Overhead-valve Design
Class III, IV, and V	Handheld	Improved Two-Stroke Design Stratified Charge and Catalyst Design Conversion of Two to Four-Stroke Design

The study is organized into three parts. Part I provides a bottom up cost analysis for non-handheld equipment engines (engine classes I and II). Within Part I, there are several chapters. Chapter 2 presents a description of small non-handheld equipment engines using the four-stroke engine, and a discussion of technical feasibility issues and emission rates. The remaining chapters in Part I provide a cost analysis for converting side-valve to overhead-valve engines (Chapter 3), a cost analysis for improving side-valve engines (Chapter 4), and a cost analysis for improving overhead-valve engines (Chapter 5).

Part II of the study provides a bottom up cost analysis for handheld equipment engines (engine classes III, IV, and V). Within Part II, there are several chapters. Chapter 6 presents a description of small two-stroke engines including technical feasibility issues and emission rates. The remaining chapters in Part II provide a cost analysis for converting two-stroke to four-stroke engines (Chapter 7), a cost analysis for improving two-stroke engines (Chapter 8), and a cost analysis for a two-stroke engine with a catalyst (Chapter 9).

Part III of the study provides cost estimates that may be incurred by the equipment manufacturer to adapt or redesign equipment to incorporate a modified engine technology (Chapter 10). For example, a modified engine that results in a larger engine may not fit under the hood of a lawn tractor. Part III also addresses user costs (Chapter 11) associated with using a modified engine. The user costs consisted of the incremental costs associated with fuel saving or consumption, and increased/decreased maintenance. Chapter 12 discusses various constraints that can potentially impact engine costs. Rule-related constraints include issues such as lead time and phase-in schedule, and timing for retiring old equipment. Manufacturer-related constraints include issues such as the effect of different production volumes and market penetration. Technology-related constraints include issues such as the feasibility of the technology and its possible use in various equipment applications. Chapter 13 summarizes the study and discusses limitations. References are provided in Chapter 14.

PART I

BOTTOM UP COST ANALYSIS FOR NON-HANDHELD EQUIPMENT ENGINES

2. NON-HANDHELD ENGINES

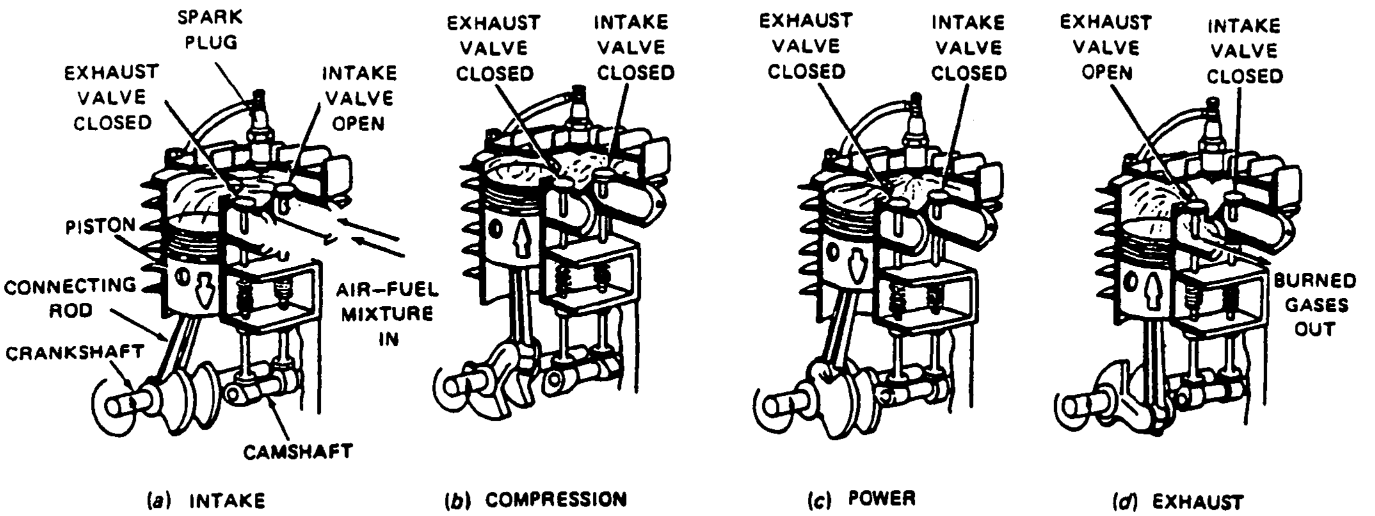
Almost all small engines used in non-handheld equipment are small, air-cooled, reciprocating Otto-cycle engines using gasoline fuel. These small engines are primarily of the four-stroke design (in contrast to two-stroke designs usually used in handheld equipment) either using side-valves (SV) or overhead-valves (OHV). This chapter discusses the operating principles and different valve configurations of small four-stroke engines. The rest of Part 1 – non-handheld engines (Chapters 3, 4, and 5) present incremental cost analyses of SV to OHV conversion, improving SV design, and improving OHV design.

2.1 Operating Principle of Small Four-Stroke Engines

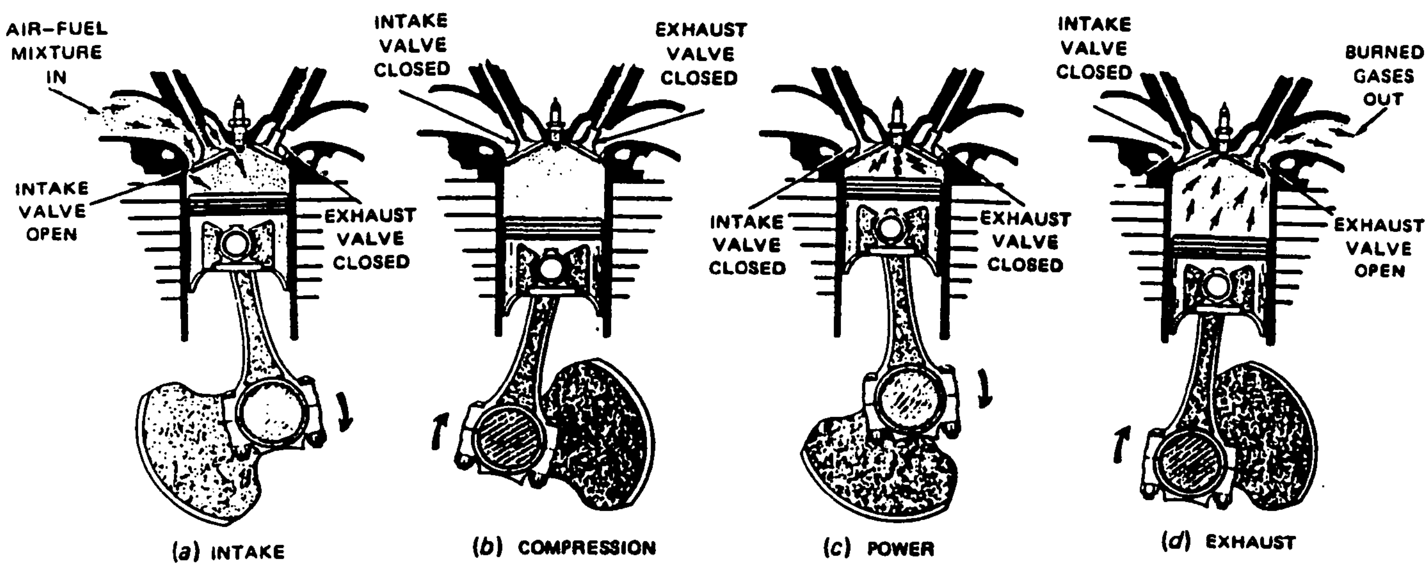
Figure 1 illustrates the operating principle of a four-stroke engine with a SV configuration (top diagrams), and an OHV configuration (bottom diagrams). As this figure shows, engine operation takes place in four distinct steps, which are intake, compression, power, and exhaust. Each step corresponds to one "stroke" of the piston, or 180° of crankshaft rotation. During the intake stroke, the intake valve opens to admit a mixture of air and fuel, which is drawn into the cylinder by the vacuum created by the downward motion of the piston. Diagram a in Figure 1 shows the piston near the end of the intake stroke, approaching bottom-dead-center. During the compression stroke, as shown in diagram b, the intake valve closes, and the upward motion of the piston compresses the air-fuel mixture into the combustion chamber between the top of the piston and the cylinder head.

The compression stroke ends when the piston reaches top-dead-center. Shortly before this point, the air-fuel mixture is ignited by a spark from the spark plug, and begins to burn. Combustion of the air-fuel mixture takes place near top-dead-center, increasing the temperature and pressure of the trapped gases. During the power stroke (diagram c), the pressure of the hot burned gases pushes the piston down, turning the crankshaft and producing the power output of the engine. As the piston approaches bottom-dead-center again, the exhaust valve opens, releasing the pent-up burned gases. Finally, during the exhaust stroke (diagram d), the piston once more ascends toward top-dead-center, pushing the remaining burned gases in the cylinder out the open exhaust port as it does so. Near top-dead-center again, the exhaust valve closes and the intake valve opens for the next intake stroke. Thus, combustion and the resulting power stroke occur only once every two revolutions of the crankshaft in a four-stroke engine.

(i) Side-valve engine

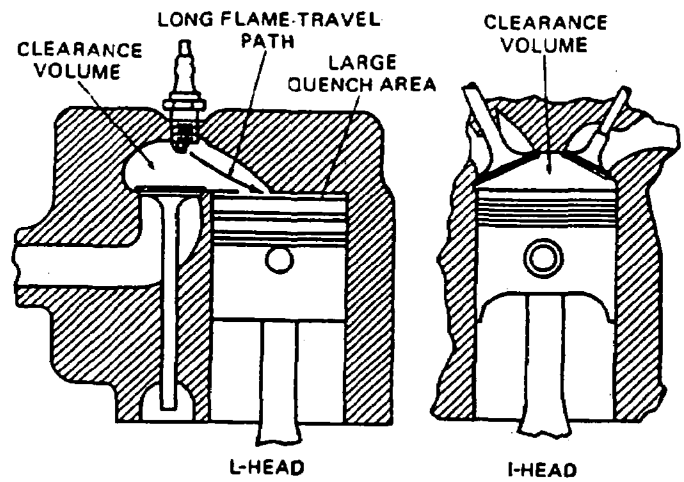


(ii) Overhead-valve engine



Source: (Crouse and Anglin, 1986)

Figure 1: Diagrams to illustrate the operating principles of four-stroke engines with side-valve and overhead-valve configurations.



Source: (Crouse and Anglin, 1986)

Figure 2: Illustrations for a side-valve (L-head) and an overhead-valve (I-head) arrangements and combustion chambers.

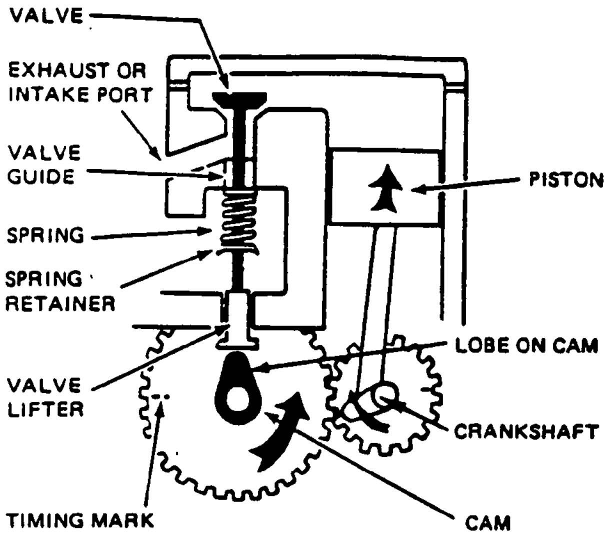
2.2 Side-Valve Versus Overhead-Valve Engines

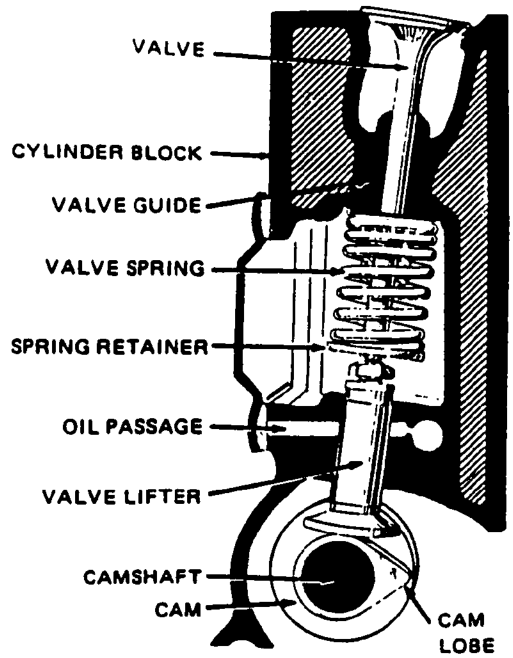
The mechanical systems required by four-stroke engines to open and close their intake and exhaust valves at the optimal time make these engines relatively complex to manufacture as compared to a two-stroke engine design. Two different types of valve arrangements are generally found in small four-stroke engines. These are the SV configuration (or L-head) and the OHV configuration (or I-head) as shown in Figure 2. Each valve arrangement, discussed below, requires a different type of valve train.

Side-Valve Engines

Most four-stroke engines found in non-handheld equipment use a SV configuration. In the SV engine, the valves are below the cylinder head of the cylinder block (see the top diagram in Figure 1). Figure 3 shows the valve train and operation of a SV engine. As this figure shows, the gear in the crankshaft drives the cam gear, which in turn rotates the cam lobes on the camshaft to push the valve lifters to lift the valves during the intake and exhaust strokes. This makes it possible to eliminate the push rods and rocker arms, and drive the valves directly from the camshaft, thus reducing the height of the engines and costs.

To accommodate the location of the valves in the engine block, the intake and exhaust ports for a SV engine must be located at the bottom of an extension of the combustion chamber, which





Source: (Crouse and Anglin, 1986)

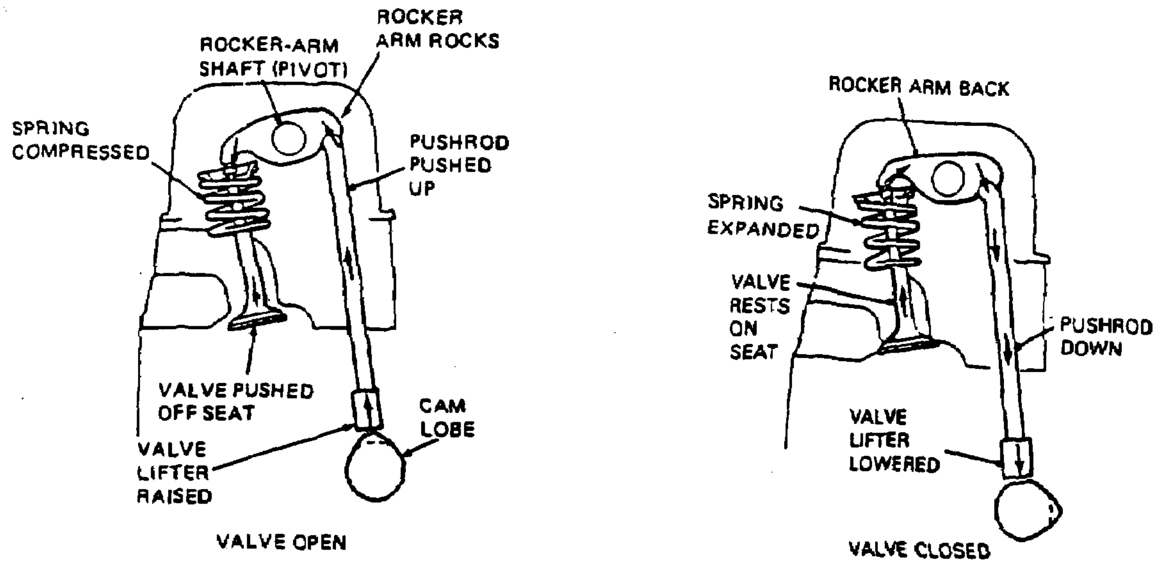
Figure 3: The valve train and operation for a side-valve engine.

projects out of the line of the cylinder bore (see the top diagram of Figure 1). This results in a long, flattened combustion chamber. High surface to volume ratio, longer flame propagation distance and longer combustion time characterize this type of combustion chamber.

Overhead-valve Engines

In the OHV engine, the valves are located in the cylinder head (see the bottom diagram of Figure 1). There are several types of OHV engines, depending on the location of the camshaft. The common camshaft location for small engines is similar to that for SV engines - at the bottom of the cylinder near the crankshaft (see Figure 4). As shown in Figure 4, the camshaft is gear-driven by the crankshaft, and cam followers in the cam assembly translate the circular motion to linear motion. This linear motion is imparted to pushrods, which act on the rocker arms to open the valves.

An alternative OHV design locates the camshaft in the cylinder head, as shown in Figure 5. This design is common in high performance engines, such as those typically found in motorcycles. For this design, the valves are opened by lobes on the camshaft, which is driven at one-half engine speed by a sprocket and chain arrangement from the crankshaft. The camshaft lobes press on the valve followers, pushing up on the rocker arms, and causing the valves to open appropriately at every second crankshaft revolution. The camshaft, valve linkage, crankshaft bearings, and pistons are lubricated by oil pumped from the oil sump at the bottom of the crankcase through a series of oil galleries. Since the camshaft is located above the cylinder, and both



Source: (Crouse and Anglin, 1986)

Figure 4: Operation of the valve train for an overhead-valve engine with a push rod design.

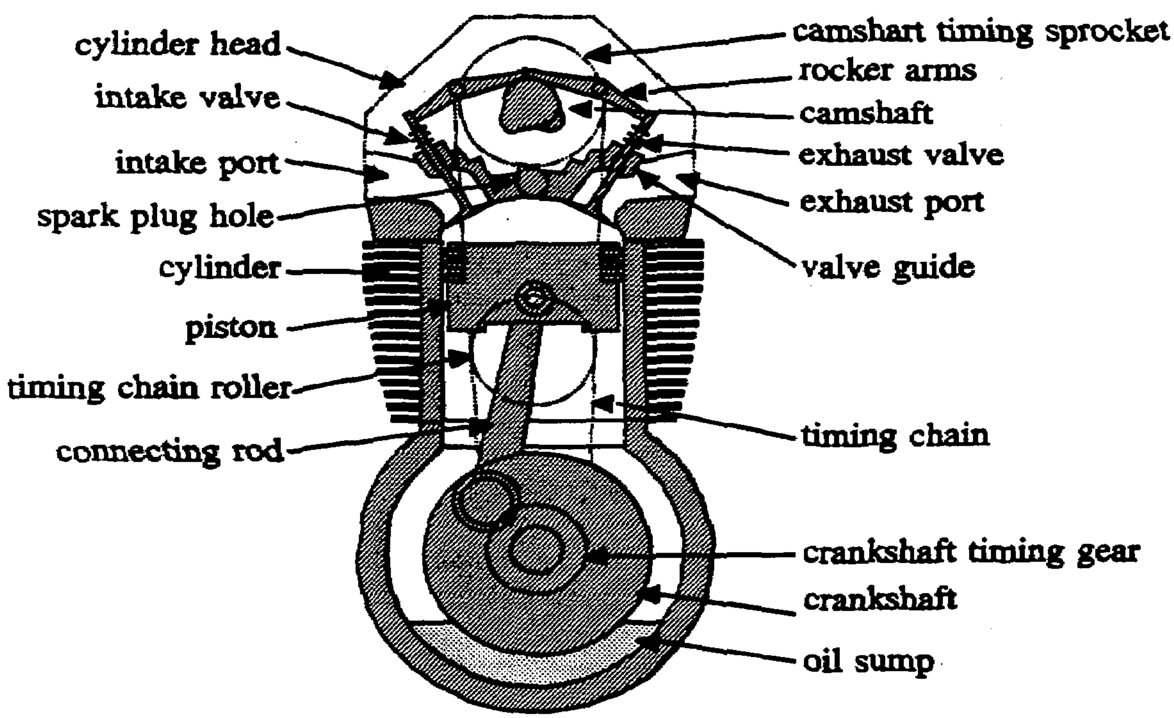
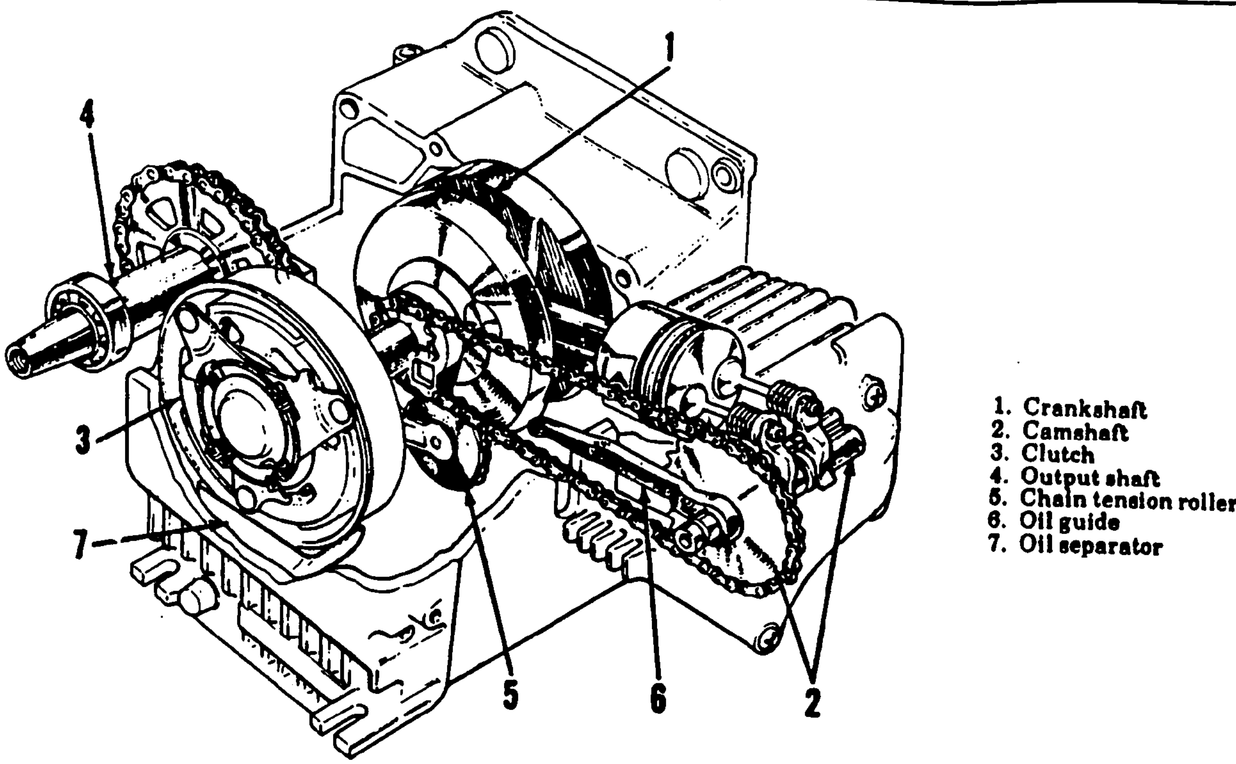


Figure 5: Mechanical layout of a typical overhead-valve, overhead-camshaft four-stroke engine.



Source: (Intertec, 1995)

Figure 6: A 1978 Honda overhead-valve, overhead-camshaft engine.

valves are controlled by a single cam, this is a "single overhead camshaft" (SOHC) engine. In some advanced four-stroke engines, the intake and exhaust valves are controlled by separate camshafts. Since it requires two camshafts, engines with this design are called double overhead cam (DOHC) engines. Because of their cost and complexity, DOHC engines are not expected to be used in utility equipment. In 1978, Honda introduced an OHV, SOHC engine for equipment applications. The schematic for this engine is shown in Figure 6.

With the EPA Phase 1 regulations taking effect in model year 1997, and the California Air Resources Board (ARB) Tier I utility equipment regulations in 1995, some engines have been redesigned to use an OHV configuration. More than 100 OHV engine models were certified with ARB in 1995.

2.3 Emissions Levels for Small Non-Handheld Engines

There are some data on emission levels for small non-handheld engines that meet EPA Phase 1 emission standards. Figure 7 shows the emissions certification data from non-handheld equipment engines.

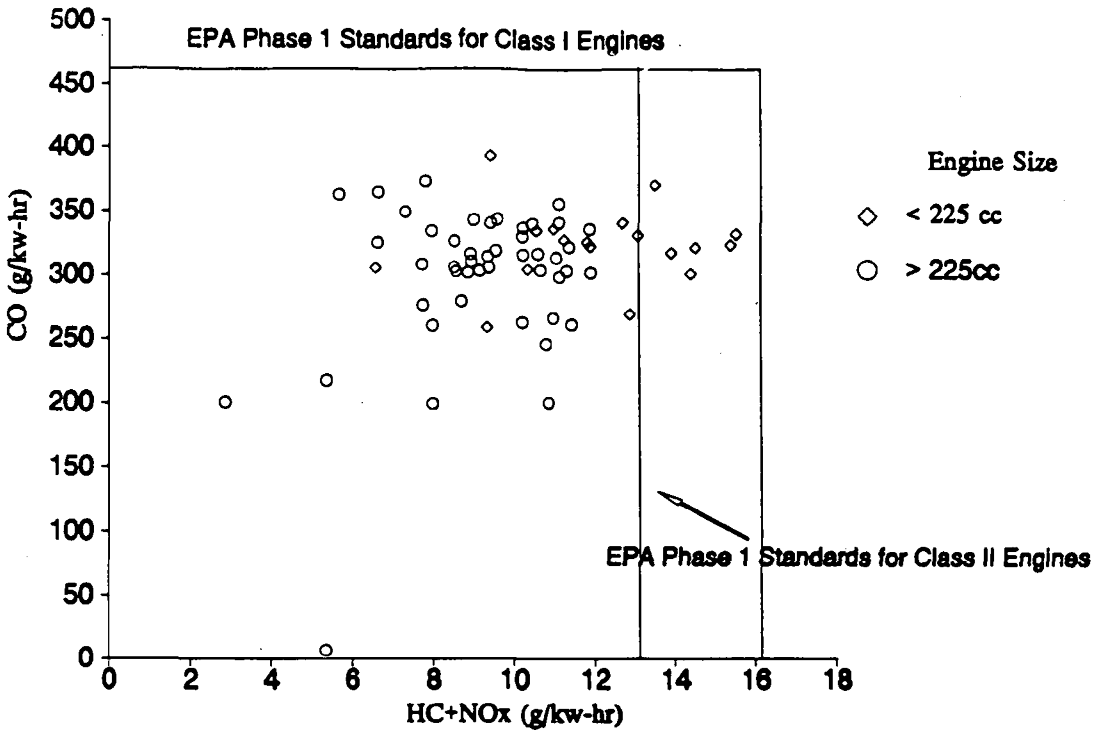


Figure 7: CARB 1995 certification data compared to EPA Phase 1 non-handheld engine standards

2.4 Emission Control Technologies for Four-Stroke Non-Handheld Engines

Small non-handheld engines pose unique problems for emission control. Because they are often used in low-cost equipment, some emission control technologies used in automotive applications (e.g., fuel injection and computer control) may not be economically feasible for these engines. The different duty cycles imposed by the different applications in which these engines are used may also pose challenges for emission control development.

Potential emission control measures for four-stroke small engines include relatively inexpensive engine modifications such as changes to valve arrangements, air-fuel mixture optimization, optimization of ignition timing, and combustion chamber improvements. Measures to reduce manufacturing variability and deposit formation in the combustion chamber can also play a significant role. More advanced technologies such as electronic control systems and catalytic converters have also been demonstrated on engines in this size range, but are considered too expensive for widespread application. Such technologies are not treated in this study, but a discussion of electronic control systems and aftertreatment technologies is provided in Appendix A for completeness' sake.

Engine Modifications

Emissions from gasoline engines can be reduced through changes in the engine design and combustion conditions. Some of the important engine design and combustion variables that affect emissions include valve arrangements (e.g., side, overhead), the air-fuel ratio λ, ignition timing, the level of turbulence in the combustion chamber, and the amount of exhaust gas recirculation, if any. Through appropriate engine design and control strategies, engine-out pollutant emissions can be reduced substantially. This involves complex tradeoffs between engine complexity, fuel economy, maximum power, and emissions.

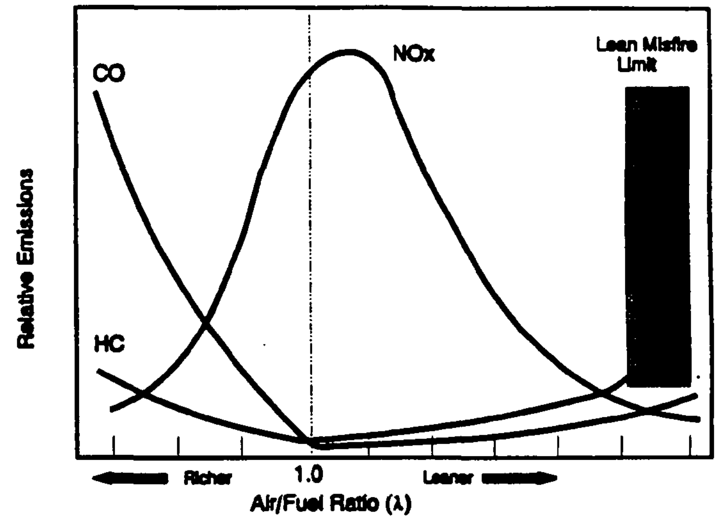


Figure 8: Effect of air-fuel ratio on SI engine emissions

__Side-valve and Overhead-valve Arrangements__ - Use of a side-valve configuration in small four-stroke engines simplifies the design of the valve train cylinder head, thus reducing manufacturing costs. The presence of the exhaust port in the cylinder block means that the side-valve engine has poorer cooling characteristics than an overhead-valve engine, however. Thus, the side-valve engine needs to run with a richer air/fuel mixture to prevent the engine from overheating, and at a lower compression ratio to prevent knock. The richer air/fuel mixture required by the side-valve engine causes it to produce higher HC and CO emissions compared to overhead-valve configuration. Also, the combustion chamber design of the side-valve engine provides a greater wall surface area and larger crevices for unburned fuel/air mixture to settle in. Since the flame is unable to penetrate these crevices, the unburned fuel in them becomes unburned HC emissions in the exhaust.

__Air-fuel ratio__ - The air-fuel ratio has an important effect on engine power output, efficiency, and pollutant emissions. Figure 8 shows the typical variation of pollutant emissions with λ for a spark-ignition engine. At λs below 1.0, there is too little oxygen to react fully with the fuel, so that CO and HC emissions increase. NO_x emissions show a peak in the vicinity of $\lambda = 1.1$, where flame temperatures are high and excess oxygen is available. For leaner mixtures, flame temperature decreases, since the chemical energy from the same amount of fuel must heat a greater mass of gas. Flame speed also decreases as the mixture becomes leaner, and ignition becomes more difficult, until combustion quality degrades to an unacceptable levels, with an accompanying increase in fuel consumption and HC emissions. This is known as the "lean ignition limit". The exact location of the lean ignition limit varies considerably, depending on the ignition system, combustion chamber design and engine rotational speed.

In the absence of emission controls, small engines are generally calibrated for maximum power output, which occurs at an air-fuel ratio somewhat rich of stoichiometric (λ between about 0.85 and 0.9). This rich mixture provides the maximum power output for a given engine size, and the excess fuel reduces the exhaust temperature - decreasing thermal stress on the engine. This is especially important in high-powered air-cooled engines. The rich air-fuel ratio required for maximum power output increases fuel consumption and HC emissions relative to those at stoichiometric conditions, and greatly increases CO emissions.

Because of the importance of air-fuel ratio control for emissions, fuel metering systems play a crucial role in the emission control system for Otto-cycle engines. Two types of metering systems are commonly used: carburetors and fuel injection. In automobiles, the use of carburetors has been completely supplanted by fuel injection systems, due to their greater precision and stability. Such systems are too expensive for small engines, however, which continue to rely on carburetors.

In a carburetor, air going into the engine is accelerated in one or more venturis, and the pressure differential in the venturi throat is used to draw fuel into the airstream and atomize it. In modern carburetors, this simple principle is supplemented by devices to provide mixture enrichment at idle and under full-load conditions, as well as during cold starts.

Carburetors are unable to maintain precise air-fuel ratio control under all conditions, and are subject to "drift" or change over time. They are not suitable, therefore, for applications which require precise and invariant air-fuel ratio control. This is one of the most important factors affecting the deterioration in Otto-cycle emissions with time, and reducing this drift without excessively increasing costs is one of the major challenges facing the small engine industry.

Exhaust Gas Recirculation - Dilution of the incoming charge with spent exhaust affects pollutant formation. In four-stroke engines, this technique is achieved through exhaust gas recirculation (EGR). The effect of exhaust gas dilution is similar to that of excess combustion air - by diluting the combustion reactants, the flame temperature and flame speed are reduced. A given volume of exhaust gas generally has a greater effect on flame speed and NO_x emissions than the same quantity of excess air (Heywood, 1988), due to the greater heat capacity of the CO_2 and H_2O contained in the exhaust and the reduced oxygen content of the charge. As with excess combustion air, too much exhaust gas recirculation leads to unacceptable variability in combustion, misfire, and increased HC emissions. The degree of exhaust gas dilution that can be tolerated before combustion begins to degrade depends on the ignition system, combustion chamber design, and engine speed. In general, ignition systems and combustion chamber designs which improve performance with lean mixtures (so-called "lean-burn/fast burn" combustion systems) also improve performance with high levels of exhaust gas dilution.

Combustion Timing - The time relationship between the motion of the piston and the combustion of the charge has a major effect on both pollutant emissions and engine efficiency. For maximum engine efficiency, combustion should be timed so that most of the combustible mixture burns near or slightly after the piston reaches the top-dead-center. A mixture that burns late in the expansion stroke does less work on the piston, decreasing fuel efficiency. A mixture that burns before TDC increases the compression work that must be done by the piston, and thus also decreases efficiency. Since the combustion process takes some time to complete, it is necessary to compromise between these two effects.

The timing of the combustion process is determined by the timing of the initial spark, the length of the ignition delay while the initial spark grows into a kernel of flame, and the rate of flame propagation through the combustion chamber. The flame propagation rate, in turn, is controlled by the geometry and turbulence level in the combustion chamber. Of these, only the timing of the initial spark is subject to control without redesigning the engine. The greater the ignition delay and the slower the flame propagation rate, the earlier (or more advanced) the initial spark must be to maintain optimum combustion timing. For typical gasoline engines, the optimum or MBT (minimum for best torque) spark advance is usually about 20 to 40° crankshaft rotation before TDC. The MBT spark advance is also a function of engine speed - at higher speeds, a greater angular advance is required, since the ignition delay time remains roughly constant.

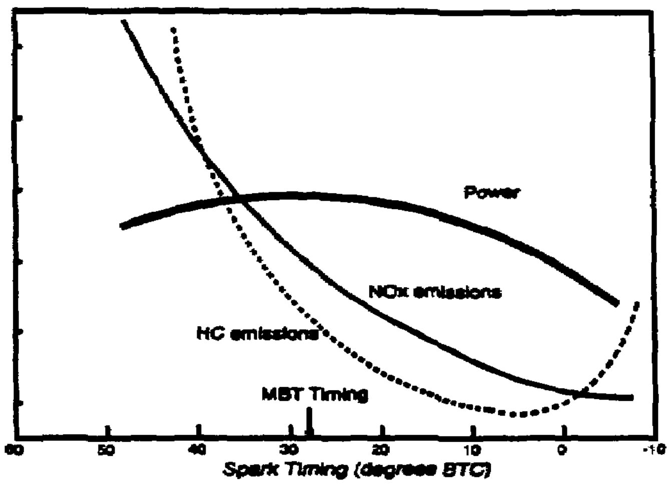


Figure 9: Typical effect of ignition timing on SI engine emissions and power output.

The portions of the air-fuel mixture that burn at or before TDC account for a disproportionate part of the NO_x emissions, since they remain at high temperature for relatively long periods. To reduce NO_x emissions, it is common to retard the ignition timing somewhat from MBT in emission-controlled engines. Moderately retarding the ignition timing also helps to reduce hydrocarbon emissions. Excessively retarded ignition timing, however, increases HC emissions, reduces power output, and increases fuel consumption, as Figure 9 shows.

<u>Combustion Chamber</u> - To reduce knock and improve efficiency, it is desirable to minimize the time required for combustion. This can be done by designing the combustion chamber to maximize flame speed and burning rate and/or minimize the distance the flame has to travel.

Figure 10 compares typical values of the fraction of fuel burned and its derivative, the combustion rate, for conventional and "fast-burn" combustion chambers. In the conventional chamber, the flame spreads radially outward at a relatively slow rate, giving a relatively long combustion time. To avoid having too much fuel burn late in the expansion stroke, it is necessary to advance the timing so that a significant part of the fuel burns before TDC.

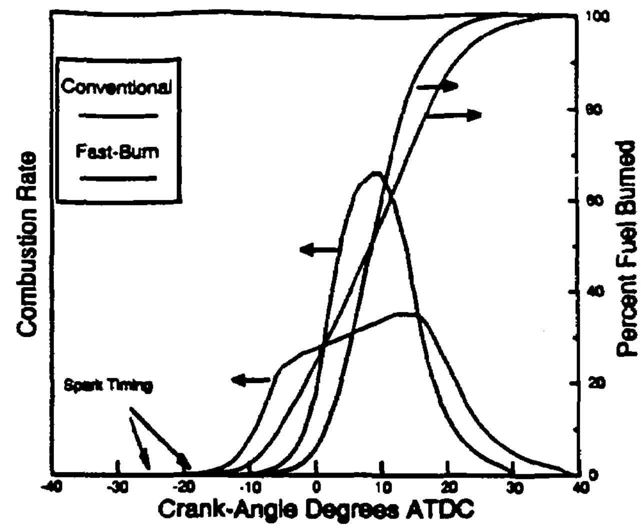


Figure 10: Combustion rate vs. crank angle for conventional and "fast-burn" combustion chambers.

With the "fast-burn" chamber, the flame spreads rapidly due to turbulent effects, giving a higher combustion rate and shorter combustion duration. With the shorter combustion time, MBT combustion timing is more retarded than for a conventional engine. Since significant combustion does not take place until after TDC, the compression work is reduced, efficiency is increased, and NOx and HC emissions are lower. There is also less fuel burned during the later stages of the expansion stroke, which contributes to better efficiency. Finally, reducing the combustion time reduces the time available for the remaining unburned mixture to undergo pre-flame reactions and self-ignite, which cause knock. Reducing the tendency of an engine to knock allows an increase in compression ratio, further increasing efficiency.

It should be noted that the combustion characteristics occurring in a "fast-burn" combustion chamber directly contrast those occurring in the combustion chamber of a side-valve engine, in which the combustion is characterized as a "slow-burn" process due to chamber configuration. However, there are ways to improve the combustion chambers in side-valve engines to reduce emissions, as well as to improve the engine performance. Xia and Jin (1991) showed that an oblique dish-shaped combustion chamber, which was designed to raise the compression ratio and burn a leaner mixture without being limited by knock, reduced the HC and CO emissions by 47 and 35 percent, respectively. The fuel consumption was also reduced by an average of 10%, and the exhaust temperature was also reduced by about 10%.

Ignition systems - The type of ignition system used, and especially the amount of energy delivered, have an important effect on the ignition delay and subsequent combustion. For any given flammable mixture, there is a minimum spark energy required for ignition. Both the minimum ignition energy and the ignition delay are lowest for stoichiometric air-fuel mixtures, and increase greatly as the mixture becomes leaner or more diluted with exhaust gas. The minimum ignition energy also increases with increasing gas velocity past the spark plug. Increasing the spark energy beyond the minimum required for ignition helps to reduce both the average length and the variability of the ignition delay.

High ignition energies are attained by increasing the spark gap (and thus the breakdown voltage) and by increasing the stored energy available to supply the arc. The former approach is the more effective of the two. To supply the necessary voltages, transistorized coil and distributorless electronic ignition systems are increasingly used. Driven by an electronic computer, these can also provide very flexible control of ignition timing. Electronic ignition timing control systems have been developed for small engines, but have not yet experienced wide commercial application, due largely to their costs. These are in the range of $10-15 per engine, compared to about $3 for typical small engine ignition systems (R.E. Phelon Co, 1995).

Anticipated Phase 2 Emissions Control Technologies for Non-Handheld Engines

The Phase 2 emission standards defined in the Statement of Principles would not require a reduction in new engine emissions compared to the Phase 1 emission standards, but would require that engines continue to meet the emission standards for a defined "useful life" period, and not only when the engines are new. Thus, the major area of focus in meeting the Phase 2 standards will be on reducing deterioration in emissions performance over time, rather than on achieving the lowest possible emissions from new engines. Among the approaches that manufacturers may employ to achieve the Phase 2 standards are: improvements in SV engines, conversion from SV to OHV, and improvement in OHV engines. The cost implications of each of these approaches are analyzed in Chapters 3 through 5.

3. COST ANALYSIS FOR CONVERTING SIDE-VALVE TO OVERHEAD-VALVE ENGINES

This chapter addresses the incremental costs of conversion from side-valve (SV) to overhead-valve (OHV) engines in non-handheld equipment. The methodology is based on a "bottom up" cost analysis comparing SV and OHV engines, including the differences in parts count and manufacturing operations. To ensure that these estimates were grounded in reality, we procured and disassembled one SV and one OHV engine in order to count and weigh the parts and to count the machining operations necessary to produce each one. Although the resulting cost analysis is based on a comparison of class I engines, we also adapted the analysis to consider the cost implications of converting a class II engine (see end of section 3.2).

3.1 Analysis of Parts Used in Side-valve and Overhead-valve Engines

Currently, OHV engines have a larger number of parts to manufacture than SV engines. To estimate the incremental cost of converting a side-valve engine design to OHV, it is necessary first to characterize the differences between them. These differences include the number and type of parts, the casting and machining operations necessary to produce these parts, and any differences in assembly requirements. To assure a firm basis for our comparison of SV and OHV engines, we purchased and dismantled two similar engines: one an SV configuration and the other an OHV. We then compared the number of parts in each engine, weighed the parts to determine the differences in material requirements, and noted the machining operations that had been used to produce each part.

Engine Selections

We analyzed the costs of converting from SV to OHV configuration for a Class I popular lawn mower engine with around five horsepower. After reviewing specifications in the sales literature, and information from a small engine service manual (Intertec, 1995a), we determined that there are five major manufacturers producing vertical shaft, OHV engines with about 5 hp. These are: Briggs & Stratton (B&S), Honda, Kawasaki, Kohler and Tecumseh. The general specifications for the engine models from these manufacturers are shown in Table 4. Exploded views for several of these engines from the Intertec manual are shown in Appendix B. Exploded views for the Honda and Kawasaki engines are not available in the manual. However, part manuals giving an engine parts breakdown for the Honda GXV140 engine and for the last Honda SV engine model G100 are included in the Appendix B.

Table 4: Major lawn mower engines with 5 to 6 hp.

	Briggs & Stratton		Honda	Kawasaki	Kohler	Tecumseh	
Model	Quantum I/C 12G700	Europa, 99700	GXV 140	FC 150V	C5	VLXL	OVRM 55
Horsepower	5	5	5	5	5	5.5	5.5
Displacement (cc)	190	147	140	153	180	207	172
Valve Arrangement	SV	OHV	OHV	OHV	OHV	SV	OHV
Weight (lb)	30	35	26	29	n/a	26	25
Height (mm)	247	260	261	271	n/a	263	269
Length (mm)	318	319	n/a	394	n/a	316	308
Wide (mm)	334	389	n/a	294	n/a	369	393
List Price	243	334	280	n/a	n/a	230	305

As shown in Table 4, only B&S and Tecumseh produce both SV and OHV engines in the 5 to 6 hp range. Based on a review of engine sales data, it was decided that the B&S engine pair was the best choice for the analysis. The SV engine in this pair was the B&S model 12 "Quantum" engine, while the OHV engine was the B&S model 997 "Europa". The model 12 is produced and sold in extremely large numbers, primarily for lawnmower use, while the model 997 is produced in smaller numbers, mostly for industrial and commercial applications, and is provided with a number of "quality" features not found in the model 12. In addition to the OHV configuration, these features include several that are not related to the choice of valve configuration, such as the use of a separate oil pump and pressure-lubricated crankshaft bearings. These features are intended to provide a longer operating life. Since the latter features are not related to the valve configuration (and are not found on OHV engines intended for the consumer lawnmower market, such as Honda's), we did not include the costs attributable to these features in the analysis.

Comparing the exploded views of the B&S and Tecumseh engines (in Appendix B) reveals that there are many common components between the SV and OHV engines. This suggests that these manufacturers have made use of the SV engine parts whenever possible when developing the OHV engines. However, it was necessary to physically examine the parts and/or review the part numbers to confirm the similarity. This was one of the reasons we decided to purchase the selected engines, and disassemble them for our analysis. After deciding which engines to use for comparison, we purchased the selected engines from a local B&S dealer. The parts lists for these engines were also obtained from a distributor, and are included in this report as Appendix B.

Additional Parts - After disassembling the engines, we counted and recorded the parts found in each one. Using this information, and confirming with the parts lists, we compiled a list of additional parts used in the OHV engine that are not found in the SV engine. This list is shown in Table 5. For each of the parts in Table 5, we estimated whether it would be more cost-effective to manufacture or purchase. The small parts, such as screws and nuts, were assumed to be purchased, while the larger and more specialized parts such as the rocker cover, rocker arms, push rod guide, and push rods would most likely be manufactured in-house. We weighed

Table 5: Information on the additional parts for the B&S Europa OHV engine as compared to the Quantum SV engine.

Item	Unit	Manufacturing Process	Part Material	Weight (lb)
Rocker Cover	1	stamping	low-carbon steel	5/16
Rocker Arm	2	stamping	low-carbon steel	3/32
Push Rod Guide	1	stamping	low-carbon steel	1/32
Push Rod	2	precision grinding	low-carbon steel	1/32
Rocker Cover Gasket	1	Purchased from suppliers		
Valve Cap	2			
Lock Screw	2			
Valve Seal	1			
Valve Stem Bushing	1			
Pivot Nut	2			
Pivot Stud	2			

the manufacturer-produced parts and determined the manufacturing processes required. This information is also presented in Table 5.

Besides the additional parts found in the valve train, the B&S OHV engine also has an oil pump assembly which is not found in the SV engine. After closely examining the OHV engine, it was determined that the pressurized lubrication system does not affect the valve train, which is still lubricated by splash lubrication as in the SV engine. The oil pump assembly in the OHV engine is used only to lubricate the crankshaft bearings. Thus, we concluded that oil pump and pressure lubrication system are not related to the choice of valve configuration, but have been included to provide longer engine life (i.e. "quality"). Honda, Kawasaki, Kohler and Tecumseh OHV engines used in lawnmowers have only splash lubrication systems. Since it is not necessary to have a pressurized lubrication system in a lawnmower engine, we did not consider the parts in the pump assembly as *required* parts for producing an OHV engine.

<u>Manufacturing Differences in Parts</u> - Besides the additional parts, there are also differences in manufacturing processes and requirements for similar components when comparing SV and OHV engines. These are due mainly to the differences in the valve train configuration. Significant differences in terms of manufacturing processes and material requirements were observed in the cylinder head and cylinder block. These differences are summarized in Table 6. We counted the number of machining operations, such as milling, boring, drilling, and tapping, required for each piece, and weighed the components to determine the material requirements. The weights for the cylinder heads and cylinder blocks for these engines are tabulated in Table 7. The cylinder head and cylinder for the OHV engine required an additional 7/8 lb of aluminum alloy. Although the engine displacement is smaller for the OHV engine, additional material was required to create the push rod passage in the cylinder block (see part number 1 for both engines in Appendix B).

Table 6: Comparison of similar components for a side-valve engine and an overhead-valve engine.

Component	SV	OHV
Cylinder Head	Simple - no intake and exhaust ports	Complex - intake/exhaust ports, valve seats, etc.
Cylinder + Crankcase	Cylinder: Complex - intake and exhaust ports, valve seats, etc. - cylinder liner Crankcase: no significant differences	Cylinder: Simple - no intake and exhaust ports - only cylinder liner Crankcase: no significant differences
Crankshaft	no significant differences	no significant differences: counterweight is slightly bigger
Connecting Rod	no significant differences	no significant differences: shorter and wider
Piston & Rings	no significant differences	no significant differences: combustion chamber on piston top
Valves	use nickel-stainless steel exhaust	could use less expensive stainless steel valve due to cooler environment

[1] Cylinder and crankcase are one unit for these engines.

Table 7: Comparison of the weights for the cylinder heads and cylinders for a side-valve engine and an overhead-valve engine.

Item	Weights (lb)		
	SV	OHV	Difference
Cylinder Head	1 5/16	1 15/16	5/8
Cylinder	4 1/2	4 3/4	1/4

The numbers of milling/boring operations for the cylinder head and cylinder block for SV and OHV engines are tabulated in Table 8. As this table shows, the OHV engine requires one more milling/boring operation than the SV engine. The drilling and tapping operations for the cylinder heads and cylinders for these engines are listed in Table 9. As this table shows, a total of 21 drilling and tapping operations are required for each engine. Thus, there is no difference in the number of drilling and tapping operations required. For drill holes without tapping, the cylinder head and cylinder for the SV engine required 10 drill holes while the OHV engine required 15 drill holes. However, the table shows that two drill holes each in the cylinder head and cylinder of the OHV engine are not used. This left only one additional drill hole as actually required for the OHV engine as compared to the SV engine. The reasons for the unused drill holes in the OHV cylinder and cylinder head are not clear, but may be related to use of common tooling or for auxiliary equipment.

In summary, about one pound of added material, one additional milling operation and one additional drilling operation are required for the cylinder head and cylinder of the OHV engine as compared to those for the SV engine. This information was used later to estimate the added material and labor costs for these components in addition to the costs for the added materials.

Table 8: Comparison of number of milling and boring operations in the cylinder head and cylinder for SV and OHV engines.

Item	SV	OHV
Cylinder Head		
Top	n/a	1
Bottom	none	1
Intake Port	n/a	2
Exhaust Port	n/a	1
Cylinder		
Top	1	1
Intake Port	2	n/a
Exhaust Port	2	n/a
Total for Cylinder and Cylinder Head	**5**	**6**

Table 9: Comparison of number of drilling and tapping operations in the cylinder head and cylinder for SV and OHV engines.

		SV	OHV
Cylinder Head			
Drilled and Tapped	Spark plug	1	1
	Rocker box fastener	n/a	4
	Intake port	n/a	2
	Exhaust port	n/a	2
	Rocker Pivot.	n/a	2
	Auxiliary	4	4
	Total	5	15
Drilled Only	Cylinder head fastener	8	4
	Lube oil passage	n/a	1
	Valve stem	n/a	2
	Unused	0	2
	Total	8	9
Cylinder			
Drilled and Tapped	Cylinder head fastener	8	4
	Intake port	2	n/a
	Exhaust port	2	n/a
	Auxiliary	4	2
	Total	16	6
Drilled Only	Lube oil passage	n/a	2
	Valve stem	2	2
	Unused	0	2
	Total	2	6
Total Both Pieces	Drilled and Tapped	21	21
	Drilled Only	11	15

3.2 Cost of Converting from SV to OHV

The cost analysis includes an estimate of the incremental variable manufacturing costs (e.g. materials and assembly labor) and fixed costs (e.g. tooling and engineering design) due to the change from SV to OHV. The incremental costs per engine produced are affected both by the size of the engine (i.e. class I or class II) and the number of engines produced. The cost analysis given in this and subsequent chapters in Part I is based on a class I engine model. A discussion of how these costs would differ for a class II engine is given at the end of each cost section. Cost estimates are also developed for a range of different annual production levels representing high, intermediate, and low volumes: 1.2 million engines per year, 200,000 engines per year, and 35,000 engines per year. The high-volume line represents a high-volume line for a class I manufacturer. The intermediate volume line can represent a high-volume line for a class II manufacturer. Further basis for these numbers is provided in Appendix D.

Variable Manufacturing Costs (Materials, Components, and Labor)

Variable manufacturing costs are those that are proportional to the number of engines produced. They include manufacturing labor, purchased parts, and raw materials. The changes in variable manufacturing costs due to changing from SV to OHV would include the additional cost of material and labor for machining the cylinder head and cylinder block, the additional costs of material and labor for producing those new parts that would be produced in-house, and the additional costs to purchase those new parts that would be purchased from outside suppliers.

Table 10: Estimation of manufacturing costs for Class I OHV engine parts made in-house

	Rocker Cover	**Rocker Arm**	**Push Rod Guide**	**Push Rod**	**Cylinder Head & Cylinder[1]**
Process	Stamping	Stamping	Stamping	Precision Grinding	Diecasting
Material	Low Carbon Steel	Low Carbon Steel	Low Carbon Steel	Stainless Steel	Al Alloy
Weight (lb)	0.313	0.094	0.031	0.031	0.875
Weight+ 10%Scrap	0.344	0.103	0.034	0.034	0.963
Material cost $/lb[2]	0.40	0.40	0.40	2.00	1.00
Material cost $/part	0.138	0.041	0.014	0.069	0.963
Labor minutes	1	1	1	1.5	3
Labor cost $/hr	15	15	15	25	25
Direct Labor $/part	0.25	0.25	0.25	0.63	1.25
Overhead @40%	0.10	0.10	0.10	0.25	0.50
Total labor+OH/part	0.35	0.35	0.35	0.88	1.75
Total mfg. cost/part	**0.49**	**0.39**	**0.36**	**0.94**	**2.71**

[1] Incremental manufacturing cost compared to SV engine components

[2] Given the relatively small contribution of material costs to the incremental cost, it was not expected that any volume savings (small vs. bulk) would appreciably change the incremental cost estimate.

Table 10 shows our estimate of the production costs for the parts that would produced in-house. Estimates of material costs were based on ranges quoted by metal suppliers contacted by telephone. Actual material prices fluctuate from day to day, but costs of $0.40 per pound for low-carbon steel and $1.00 per pound for aluminum alloys are typical (Capital Steel Co., 1996). Estimates of labor time requirements were developed with the assistance of standard references on manufacturing cost estimation (Ostwald, 1984; Winchell, 1989). Stamping will take less time than precision grinding. Die casting and subsequent machining would take the longest time, accounting for the milling and drill/tapping operations.

The costs of hourly labor include wages and fringe benefits. We estimated these at $15 per hour for relatively unskilled tasks such as operating the stamping press. According to the 1992 Census of Manufactures, average 1992 hourly wages in SIC 3524 (Lawn and Garden Equipment) were $10.71. Allowing for inflation and 30% for fringe benefits, this would be about $16 per hour in 1996, which is consistent with our estimates. Labor for more skilled operations, such as a precision grinding, milling, and drilling were estimated at $25 based on the average rates for machinists.

The labor overhead rate for small engine manufacturing was assumed to be 40 percent of the cost of direct labor used on emission related components (Lindgren, 1977).

Table 11: Estimation of incremental variable manufacturing cost for Class I OHV engines compared to SV engines.

	Cost/Piece	Pieces/Engine	Total
Rocker Cover	0.49	1	0.49
Rocker Arm	0.39	2	0.78
Push Rod Guide	0.36	1	0.36
Push Rod	0.94	2	1.89
Rocker Cover Gasket	0.25	1	0.25
Valve Cap/key	0.10	2	0.20
Lock Screw	0.05	2	0.10
Valve Seal	0.10	1	0.10
Valve Stem Bushing	0.30	1	0.30
Pivot Nut	0.25	2	0.50
Pivot Stud	0.25	2	0.50
Cylinder Head & Cylinder	2.71	1	2.71
Total Parts Cost			8.18
Added Assembly Labor			
Labor minutes			3
Labor Cost, $/hr			15
Direct Labor Cost, $			0.75
Overhead @40%, $			0.3
Total Labor + OH, $			1.05
Total Added Variable Manufacturing Cost			9.23

Table 11 shows our estimate of the total change in variable manufacturing costs per engine due to the change from SV to OHV. In addition to the costs of manufacturing the parts, the total change in variable costs also includes the purchase cost of those additional parts obtained from outside suppliers. Our estimates of the prices for each of these are shown in Table 11. The costs of purchased parts were estimated based on our own experience, conversations with part suppliers, and conversations with other knowledgeable parties in the small engine industry (e.g. *Conley, 1996; Huffman,* 1996). In addition to the increased part costs, we estimate that the more complex cylinder head and valve train would require three extra minutes of assembly labor, costing $1.05 with overhead (Ostwald, 1984; Winchell, 1989). The total change in variable manufacturing costs, therefore, comes to $9.23.

Since the variable costs are expressed on a per-engine basis, there would be relatively little difference in these costs between the large and small manufacturer. Because of learning-curve effects and economies of mass production, we would anticipate that the actual variable costs for the large manufacturer in the 1.2 million engine case would be slightly smaller, but these differences are difficult to quantify without much more detailed information.

Fixed Costs

Fixed costs are costs that must be incurred to produce an engine model, regardless of the number of units produced. Fixed costs associated with the conversion from SV to OHV include engineering design and testing costs; the costs of the special tooling, molds, and other equipment needed to produce the changed or additional parts; the costs of changing the production line to accommodate the changes in the assembly process and in the size and number of parts; and the costs of updating parts lists and technical manuals to reflect the changed design. Table 12 shows the estimated fixed costs due to changing from SV to OHV at each of the three production levels considered.

Since all of the major small engine manufacturers are presently producing OHV engines for at least part of their product line, there would be no need for research and development to develop this technology. Thus, no costs are allocable to R&D. However, we estimate that the necessary changes in engine design would require the efforts of about four engineers for

Table 12: Estimated fixed costs for the change from SV to OHV class I engine.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (4 years @ $100,000)	400,000	400,000	400,000
Number of Tests	400	400	400
Test Cost ($)	300	300	300
Testing costs	120,000	120,000	120,000
Other engineering	100,000	100,000	100,000
Total Engineering	620,000	620,000	620,000
Technical support			
Training/Tech. Pubs	500,000	200,000	200,000
Tooling Costs			
New Master Dies			
Cylinder head	60,000	60,000	60,000
Cylinder block	40,000	40,000	40,000
Connecting rod	15,000	15,000	15,000
Piston	25,000	25,000	25,000
Crankshaft	25,000	25,000	25,000
Rocker arm	30,000	30,000	30,000
Rocker cover	50,000	50,000	50,000
Push rod guide	10,000	10,000	10,000
Setup changes	100,000	50,000	50,000
Total tooling	355,000	305,000	305,000
Total Engine-Specific	1,475,000	1,125,000	1,125,000
Amortized over 5 yrs	379,211	289,229	289,229
New Machine Tools	980,000	230,000	90,000
Amortized over 10 yrs	152,704	35,054	13,717
Total Fixed Cost/Yr	531,915	324,283	302,946
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.44**	**1.62**	**8.66**

about one year. This estimate is based on consideration of the technical requirements and the length of process necessary for the design change (B&S, 1996). For typical engineering salaries and overhead rates, the cost of an engineer working full-time for a year (including salary, benefits, physical and administrative overhead, and other costs) is estimated to be about $100,000. This is a conservative estimate for the small engine industry based on the benefits/overhead in the automobile industry (with which the small engine industry competes for engineering talent). With this loaded engineering cost, the total cost of engineering staff time for engine redesign would be about $400,000.

Additional costs would be incurred for testing of prototype engines, special materials, travel, and other similar expenses associated with the design changes. We estimate that engine calibration would require about 200 emission tests per engine model and another 200 tests for durability and reliability. We estimated the manufacturer's cost per test at about $300, based on the analysis in Table 13. This is also consistent with the lower end of the range of testing costs obtained in discussions with several independent test laboratories. At $300 per test, the 400 emission tests would cost about $120,000. We estimated that the costs of test engines, travel, test materials and so forth would amount to another $100,000, so that the total engineering design costs would be about $620,000. These costs would not be greatly different between the three different production levels.

Table 13: Estimated cost of emission testing.

Capital Cost	
Analyzer bench	100,000
Dynomometer	50,000
Test cell	50,000
Misc. Instruments	60,000
Total Capital Cost	260,000
Amortized 5 yrs @ 9%	66,844
Operating Costs	
Test engineer (1/2)	50,000
Technician	60,000
Supplies/Repairs	40,000
Total Annual Cost	216,844
Tests/day	3
Tests/yr	750
Cost/test	289

Changes in the engine hardware would require corresponding changes in the company's technical support services - service manuals, technical training, etc. A source at Honda (1996) indicated that the costs of completely revising technical documentation and training dealers for a major engine change were of the order of $500,000, while the costs of issuing a technical bulletin for a minor change were around $10,000. Based on this information, we estimated the technical support costs for the SV to OHV conversion at $500,000 for the high volume engine line, and at $200,000 for the smaller-volume engine lines. The costs are lower for the smaller lines, as these would have fewer manuals to print and fewer dealers to train.

The production changes involved in going from side-valve to overhead-valve would also require tooling costs. The main tooling costs would be the production of new master designs for the dies used to cast the cylinder head, cylinder block, connecting rod and piston. After discussing with some die manufacturers (Spec Cast, Prince Machine and Muller Weingaren 1996), we estimate these costs at $60,000 for the cylinder head, $40,000 for the cylinder block, and $15,000 and $25,000 for the much simpler connecting rod and piston castings, respectively. New masters would also be required for the stamping dies for the new stamped parts. Stamping dies are more expensive than the casting dies. Based on our conversations with stamping die manufacturers

(Hess-MAE and Sheffield Progressive 1996), we estimate $10,000, $30,000, $50,000 for push rod guide, rocker arm, and rocker arm cover dies, respectively.

Note that we have not included any costs for the actual production of new casting dies, but only the master designs from which the dies are produced. That is because casting dies wear out and must be replaced periodically in any event, so that their replacement with a new design would not necessarily involve any incremental cost except for the new master.

The few additional machining operations required for the OHV cylinder and cylinder head would not likely require new machine tools, but it would be necessary to change fixtures, jigs, and material handling equipment and to modify production line flow to incorporate the new and changed parts and the new assembly procedures. The costs of these changes include mostly labor and engineering time, retraining costs, and the cost of lost production while the assembly line is down. These are lumped together as "setup" in the table. Setup costs are difficult to estimate, as they are highly plant- and process-specific. We estimate these costs setup cost at $50,000 for the two lower-volume engine lines, and $100,000 for the high volume engine line, based on our judgement of the relative complexity of the changes needed. Smaller-volume engines tend to be produced using more flexible procedures, so that the production changes are easier to accommodate.

Total engine-specific costs (excluding the costs of new machine tools) are totalled at $1.475 million for the large volume engine line, and $1.125 million for the two smaller volume engine lines. These costs were amortized over five years at a cost of capital of 9%. The five year amortization period reflects the typical time between model changes. The assumed 9% cost of capital is consistent with information from the industry. Capital costs would not be much different between the large- and small-volume production cases, as even most small-volume engine manufacturers are divisions of large companies, and thus have access to relatively low-cost capital.

In addition to the engine-specific costs, the production of the new parts in-house would require that some new machine tools be purchased (assuming that all existing machine tools are fully utilized). For the high-volume engine line, we estimated that ten new 50-ton stamping presses would be required for the stamped parts, at $50,000 each. This estimate is based on an assumed throughput of two stampings per press per minute, with the presses operating two shifts for a total of 14 hours per workday. We also estimate that 12 new CNC grinders would be required for the pushrods, at a cost of $40,000 each. These estimates are based on typical price ranges for machine tools given by industry sources. The total cost of the new machine tools required would be $980,000 for the 1.2 million engine per year line. For the 200,000 engine per year case, we estimate that three presses and two grinders would be required, for a total cost of $230,000. For the 35,000 unit case, we assumed that the stamped parts would be produced in batches, requiring only one new press and one grinder for a total of $90,000.

The costs of the new machine tools required were amortized over 10 years at 9%. Ten years is about the economic lifetime of a machine tool before it is either worn out or made obsolete by advancing technology.

Table 14: Summary of the variable and fixed costs for converting SV to OHV Class I engines.

	Case 1	Case 2	Case 3
Total Added Manufacturing Cost	9.23	9.23	9.23
Fixed Costs	0.44	1.62	8.66

The total amortization of the fixed costs amounts to about $532,000 per year for the 1.2 million unit case, $324,000 per year for the 200,000 unit case, and $303,000 for the 35,000 unit case. Dividing by the number of units produced per year results in fixed costs of $0.44 per engine for the 1.2 million unit model, $1.62 per engine for the 200,000 unit model, and $8.66 for the 35,000 unit model. Table 14 shows a summary of the hardware/assembly costs and fixed costs for converting SV to OHV Class I engines for the three cases.

Adapting the Cost Estimate for Class II Engines

We expect that the conversion of a class II engine may have larger incremental costs than a class I engine. In terms of variable costs, the material mass requirements for engine parts made in-house would be roughly triple those of a class I engine (based on engine dry weight comparison of a 5 hp and 14 hp engine). This would add $2.67 per engine to the costs, giving a total material cost per engine of $4.01. The labor to make the parts is expected to be the same. The prices of purchased parts would also increase to reflect the increased material requirements. We estimate this increase at about 50%, based on the ratio of material cost to total cost for the parts made in-house. The cost of purchased parts would thus increase by $.98. The total change in variable cost would then be about $3.65 per engine, bringing the total variable cost to about $12.88.

The fixed costs for developing the engine design and changing the production process would be essentially the same for the larger class II engines. The costs of preparing master dies, for example, are determined more by the complexity of the part than by its size. Similarly, differences in parts size would not have a significant effect on machine tool costs, as the parts would still be within the size range for standard machine tools. A more significant effect would result from the lower production volumes typical for class II engines, which commonly range from 35,000 to 200,000 engines per year (i.e. the two lower production ranges considered in our analysis). The fixed costs per engine would thus be around $1.62 at 200,000 engines per year, and $8.66 at 35,000 engines per year.

Possible Developments to Reduce Incremental Conversion Costs

The incremental costs estimated above for shifting and SV engine design to OHV do not account for possible cost savings due to redesign and re-engineering of production processes to take advantage of improvements in manufacturing techniques. Many existing SV engine designs are quite old, and incorporate old manufacturing technology. By redesigning the engine (i.e., fewer parts) and its production processes, manufacturers might be able to achieve significant savings in production costs, and a number of engine manufacturers are doing so. Advances in material minimization or the use of lighter and cheaper materials could reduce costs further. In some cases, manufacturers have indicated that the cost savings equal or even exceed the incremental costs due to the change from SV to OHV. We have not attempted to account for these potential savings in this report.

Possible Cost Saving Through Learning Curve Effect

The incremental cost for converting from SV to OHV should be less for every year of production as a result of the phenomenon known as the "learning curve." A general 'rule of thumb' used by EPA in the past (EPA, January 1996) is that for every doubling of production, the costs are reduced by 20 percent. This is primarily applicable to variable (labor, material) costs. For example, in the second year of production (assuming same production) the variable costs should be reduced by 20 percent over the first year. In contrast to variable costs, fixed capital costs are usually one time costs spread over several years and therefore are not subject to the rule. However, high-volume engine lines may experience this type of cost reduction for some fixed costs because the engine dies are often replaced more than once a year (see Chapter 12 discussion on retirement of manufacturing equipment). This cost savings learning curve is applicable to the other engine modificaiton technologies.

Possible Actions by Small Manufacturers to Reduce Costs to Convert SV to OHV

There may be only a few manufacturers in the non-handheld engine market that can be characterized as small manufacturers. Most small engine manufactures with small market share (Wisc-Teledyn, Kawasaki) are medium to large companies with the ability to afford extensive capital investment. We expect that any actual small engine manufacturer, faced with the prospect of having to convert a SV family line to an OHV family line, may not go about it the same way as it had in the past in producing the SV family line. We anticipate that the small engine manufacturer may make certain decisions to reduce the costs of this conversion. For example, the small engine manufacturer may not be able to afford the capital investment necessary to purchase new machine tools to make their own cylinder head and block (which is necessary for a new OHV design). Also, even if the small manufacturer wants to purchase the machine tools, the small manufacturer will likely have to pay a higher interest rate for capital investment. Consequently, the small manufacturer may contract for services from a machine tool company to produce the cylinder head and block. The machine tool company may be able to make these engine parts cheaper because the company's big machines can be used for several jobs from other clients. Even with the markup from the machine tool company, the small manufacturer could gain modest savings per engine.

Additionally, the small manufacturer may purchase a license for an OHV engine design rather than incur the engineering labor to develop the design itself. Although this is a one time cost, saving per engine could occur in reduced engineering design costs. Also, instead of incurring the costs for developing new training/technical/catalogue publications, the small manufacturer may purchase and adapt the publications from the licensing company. This could perhaps have additional savings over the estimated costs for a small manufacturer to develop their own training/technical/catalogue publications. Finally, the small manufacturer may find ways to consolidate low-production lines by modifying a higher production engine (i.e., add governor or have smaller stroke to make lower power engine line from higher power engine). We assume that some of the above cost savings decisions would be implemented by a small manufacturer.

4. COST ANALYSES FOR IMPROVING SIDE-VALVE ENGINES

This chapter presents the cost analysis for improvements in side-valve engine technology. Potential improvements in SV engine technology to reduce emissions include:

- improvement in combustion and intake systems
- improvement in spark ignition and timing
- optimization of valve timing and cam design
- improvement in piston and ring designs
- improvement in manufacturing variability
- improvement in carburetor

Similar to the cost analysis for the SV to OHV conversion, we assessed the incremental variable and fixed costs for each of these technologies. For all technologies except the carburetor improvement, we based our analysis on the same three scenarios considered in the preceding chapter: engine models with production of 1.2 million, 200,000, and 35,000 units per year, respectively. Since a single carburetor model may be used on many engine lines, we analyzed only a single scenario for carburetor improvements. This scenario assumed annual production of four million units per year for a manufacturer with a large market share.

4.1 Improvement in Combustion and Intake Systems

Since the conditions in the intake system affect the combustion process, combustion and intake systems are treated together in the research, design and development processes. Minor changes in the intake and combustion chamber design for SV engines can produce a more homogeneous mixture and better combustion, thus helping to reduced emissions. Improvements in this area would not affect the number of parts used in the engine, but only the geometry of the existing parts. Examples would include a new combustion chamber geometry with smaller surface to volume ratio and/or with a squish band to improve mixing, or changing the geometry of the intake to induce more swirl to the combustion chamber. These changes are not expected to affect variable production costs significantly. (Although engine manufacturers might choose to take advantage of the opportunity to combine parts or substitute newer production processes where these would be profitable, any such changes would be highly engine-specific, and we have not attempted to account for them.) Although material requirement might change slightly, these changes could be in either direction, and would likely be minimal in either case. Thus, the only quantifiable costs incurred as a result of combustion and intake system improvements would be the fixed costs of changing the production process.

Table 15 shows the estimated fixed costs associated with each engine production level. The design challenges in developing an improved combustion and intake system for an SV engine are modest. We estimate that this development would require about one person-year of engineering time, at a cost of about $100,000. Engine calibration would require about 100 emission tests per engine model, with another 100 tests for durability and reliability assessment. At $300 per test, the emission tests would cost about $60,000. Other engineering-related costs such as model building, special materials, test engines, and travel are estimated at $25,000.

Changes in the design of the combustion chamber and intake systems would require a one-time cost to revise parts and stocks listings. Based on the information from Honda (1996), we estimated that these changes would cost about $20,000, or the equivalent of two service bulletins.

Table 15: Estimated fixed costs for the changes in improving combustion chamber and intake systems.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (1 year @ $100,000)	100,000	100,000	100,000
Number of Tests	200	200	200
Test Cost ($)	300	300	300
Testing costs	60,000	60,000	60,000
Other engineering	25,000	25,000	25,000
Total Engineering	185,000	185,000	185,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
New Master Dies			
Cylinder head	25,000	25,000	25,000
Piston	25,000	25,000	25,000
Total Tooling	50,000	50,000	50,000
Machine Tool Setup	50,000	25,000	25,000
Total Engine-Specific	305,000	280,000	280,000
Amortized over 5 yrs	78,413	71,986	71,986
New Machine Tool	0	0	0
Amortized over 10 yrs	0	0	0
Total Fixed Cost/Yr	78,413	71,986	71,986
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.07**	**0.36**	**2.06**

Changes in combustion chamber and intake system geometry would involve tooling costs. The main tooling costs would be the production of new master designs for the dies used to cast the new cylinder head and piston with improved combustion chamber designs. Based on information from die manufacturers (Spec Cast, 1996; Prince Machine, 1996; Muller Weingaren, 1996) we estimated these costs at $25,000 for the cylinder head die, and $25,000 for the piston casting. We also estimated that it would cost $50,000 and $25,000 to change the machining fixtures for the high-volume line and the two low-volume lines, respectively. No new machine tools would be required.

Total engine-specific costs are estimated at $305,000 for the 1.2 million unit case, and $280,000 for the 200,000 and 35,000 unit cases. These costs were amortized over five years at 9%. The total amortized fixed costs amount to about $78,400 per year for the 1.2 million unit case and $72,000 per year for the other two cases. Dividing by the number of units produced results in fixed costs of $0.07 per engine for the 1.2 million unit case, $0.36 per engine for the 200,000 unit case, and $2.06 per engine for the 35,000 unit case. The costs for similar modifications to a class II engine would be the same.

4.2 Improvement in Spark Ignition and Timing

Similar to the case of combustion chamber and intake systems improvement, changes in spark ignition and timing would not require additional parts or extensive engine redesign. The spark timing can be changed by changing the location of the stator and flywheel key on the crankshaft. Spark ignition can be enhanced by using a different spark plug or ignition module. The differences in cost to the engine manufacturer of changes in ignition modules or spark plugs are difficult to predict, and would be small in any case. Changes in ignition timing would involve only fixed costs. Our cost estimates are shown in Table 16.

Table 16: Estimated fixed costs for the changes in improving spark ignition and timing.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (1/3 year @ $100,000)	33,000	33,000	33,000
Number of Tests	100	100	100
Test Cost ($)	300	300	300
Testing costs	30,000	30,000	30,000
Other engineering	10,000	10,000	10,000
Total Engineering	73,000	73,000	73,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
Machine Tool Setup	10,000	5,000	5,000
Total Engine-Specific	103,000	98,000	98,000
Amortized over 5 yrs	26,481	25,195	25,195
New Machine Tools	0	0	0
Amortized over 10 yrs	0	0	0
Total Fixed Cost/Yr	26,481	25,195	25,195
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.02**	**0.13**	**0.72**

The development work to optimize the spark ignition system and ignition timing was estimated to require about four person-months of engineering time, and about 100 emissions tests. Other engineering-related costs were estimated at $10,000. Costs of changing technical documents were estimated at $20,000, or the equivalent of two service bulletins. No new tooling would be required, but some changes in the setup of the existing tooling would be needed to accommodate the changed location of the flywheel key. Total engine-specific costs are estimated at $103,000 for the 1.2 million unit case, and $98,000 for the other two cases. Amortizing these costs over five years at a cost of capital of 9%, and dividing by the annual production results in fixed costs of $0.02 per engine for the 1.2 million unit case, $0.13 per engine for the 200,000 unit case, and $.72 per engine for the 35,000 unit case. The costs for similar modifications to a class II engine would be the same.

4.3 Optimization in Valve Timing and Cam Design

Optimization in valve timing and cam design would generally require only research, design and development costs. In our discussions with one engine manufacturer, however, it was indicated that it might be necessary to change the camshafts in some engine models. These models use nylon cam lobes that are pressed onto a steel tube or rod, and the concern is that the nylon may not be durable enough to ensure stable emissions over the useful life of the engine. Camshafts are traditionally made of cast iron, which must then be machined to exact dimensions. Some recent engines, such as the Ryobi hand-held four-stroke, use powder-metal camshafts, however. This process is less expensive than casting and machining a cast iron camshaft, and should give dimensional accuracy at least equal to that of the press-fit nylon cam lobes and much better durability. We were not able to estimate the variable cost differences between a powder-metal camshaft and the present nylon/steel camshaft with any accuracy, due to lack of information about the production process for the latter. Since the powder-metal part would be made to final shape in a single operation, without machining, there should be a saving on labor compared to the present design. Material costs for the two designs would be similar. Thus, we would expect a small net reduction in variable costs with the powder-metal part. For conservatism, however, we have assumed a zero savings in variable costs.

Our estimates of the fixed costs involved in optimizing valve and camshaft design are tabulated in Table 17. Development of the optimum valve timing and design of the powder-metal camshaft are estimated to require about one year of engineering time, at a cost of $100,000. About 200 emission tests would be required, at a cost of $60,000. Other engineering-related costs (prototype camshafts, other tests, etc.) were estimated at $25,000. Total engineering costs are estimated at $185,000.

Molds for powder-metal forming are less expensive than for die-casting or stamping, ranging from $3,500 to $8,000 (Monaich, 1996). We assumed a cost near the top of this range. The cost of altering the production process to accom-

Table 17: Estimated fixed costs for optimizing valve timing and cam design for SV engines.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (1 year @ $100,000)	100,000	100,000	100,000
Number of Tests	200	200	200
Test Cost ($)	300	300	300
Testing costs	60,000	60,000	60,000
Other engineering	25,000	25,000	25,000
Total Engineering	185,000	185,000	185,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
New Master Dies			
Camshaft	8,000	8,000	8,000
Total Tooling	8,000	8,000	8,000
Machine Tool Setup	20,000	10,000	10,000
Total Engine-Specific	233,000	223,000	223,000
Amortized over 5 yrs	59,903	57,332	57,332
New Machine Tools	565,000	282,500	141,250
Amortized over 10 yrs	88,038	44,019	22,010
Total Fixed Cost/Yr	147,941	101,351	79,341
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	0.12	0.51	2.27

modate the change in camshaft production methods are estimated at $20,000 for the high-volume engine line, and $10,000 for the low-volume lines. Thus, the total engine-specific costs are estimated at $233,000 for the 1.2 million unit case and $223,000 for the other two.

The switch to powder-metal production would require a substantial investment in new production machinery. The cost of the presses to compact the green molds ranges from $50,000 to $190,000 (Fulesday; 1996). We estimated that one press would be required for the 1.2 million unit case, at a cost of $190,000. The cost of the sintering furnace is about $300,000 (C.I. Hess, 1996). Powder metal hoppers and handling equipment would add about $75,000, for a total cost of $565,000. For the 200,000 unit case, we assumed that production would be split between two similar engine lines, so that the total cost allocable to each line would be $282,000. For the 35,000 unit case, we assumed that it would be split four ways, so that the cost allocable to one line would be $141,000 (In most cases, manufacturers will produce more than one engine line, making it economic to share powder-metal parts production between lines. Where that is not the case, the manufacturer would probably choose to contract with an external supplier to produce the parts). Total fixed cost amortization amounts to $148,000, $101,000, and $79,000 per year for the 1.2 million, 200,000, and 35,000 unit cases, respectively. Dividing by the number of units, the fixed costs would be $0.12, $0.51, and $2.27, respectively. These costs would not be significantly different for a class II engine.

4.4 Improvement in Piston and Ring Designs

In order to assure that an engine would meet emission requirements throughout its lifetime, one manufacturer (Briggs and Stratton, 1996) indicated that it is necessary to reduce the amount of lubricating oil that enters the combustion chamber past the piston rings and along the valve stems. This oil contributes to the formation of carbon deposits, which degrade the combustion and emission characteristics. Reducing the oil loss into the combustion chamber would therefore improve emissions durability, as well as reducing maintenance costs to the consumer. This will require higher manufacturing tolerances to produce better quality piston and ring packages. The same manufacturer indicated that in order to produce a better quality piston it would be necessary to change from a die-cast piston to one produced by permanent-mold casting. This would require procuring the pistons from an external supplier. The manufacturer estimated the incremental cost of the permanent-mold piston as about $1.50 to $2.00, and that of the ring package at about $0.50. For our cost analysis, we took the midpoint of the manufacturers' estimated range of piston costs, or $1.75.

Some SV engines have valve stem bushings only on the intake valve stem, and not on the exhaust valve stem. To reduce the amount of oil entering the combustion chamber along the exhaust valve stem, it would be necessary to add a bushing to the exhaust valve stem as well. We estimate the cost of the bushing at $0.30. We also assume that it would take an additional one-half minute of labor to account for handling and pressing the bushing into the cylinder block. The resulting cost estimates are summarized in Table 18.

Fixed cost estimates are summarized in Table 19. We estimate that the development of the improved engine and ring package and the exhaust valve bushing would require about one person-year of engineering time, plus extensive durability testing. We estimate the cost of the durability testing at $100,000. About 100 emission tests would also be required, so that total testing costs would be about $130,000. Other engineering costs are estimated at $15,000, for a total engineering cost of $245,000. Training and technical support costs are estimated at $20,000, or about enough to send out two service bulletins.

Table 18: Incremental variable manufacturing cost for improving piston and ring design and adding exhaust valve stem bushing for SV engines.

	Cost/ Piece	Pieces/ Engine	Total
Piston	1.75	1	1.75
Piston Rings	0.50	1	0.50
Valve Bushing	0.30	1	0.30
Total Parts Cost			2.55
Added Assembly Labor			
Labor Minutes			0.5
Labor Cost, $/hr			15
Direct Labor, $			0.125
Overhead @40%, $			0.05
Total Labor +OH, $			0.175
Total Added Variable Manufacturing Cost			2.73

The changes in the piston would require matching changes in the connecting rod design, thus making necessary a new master die for the connecting rod. Fairly extensive changes to the assembly and component handling processes would also be required to accommodate the changes in piston and ring pack design, and to press the exhaust valve stem bushing into the exhaust port. These changes are estimated to cost $50,000 for the 1.2. million unit case, and $25,000 for the two lower-volume cases. Thus, the total engine-specific costs are estimated at $330,000 for the 1.2 million unit case, and $305,000 for the other two cases. Amortizing these costs over five years at a cost of capital of 9%, the total amortized fixed costs amount to about $85,000 per year for the 1.2 million unit case and $78,000 per year for the other two. Dividing by the number of units produced results in fixed costs of $0.07 per engine for the 1.2 million unit case, $0.39 per engine for the 200,000 unit case, and $2.24 per engine for the 35,000 unit case. Table 20 shows a summary of the hardware/assembly costs and fixed costs for improving piston and ring designs for SV engines for the three cases.

Table 19: Estimated fixed costs for the changes in improving piston and ring designs for SV engines.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor+OH *(1 year @ $100,000)*	100,000	100,000	100,000
Emission Testing	30,000	30,000	30,000
Durability Testing	100,000	100,000	100,000
Total Testing costs	130,000	130,000	130,000
Other engineering	15,000	15,000	15,000
Total Engineering	245,000	245,000	245,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
New Master Dies			
Connecting Rod	15,000	15,000	15,000
Total Tooling	15,000	15,000	15,000
Machine Tool Setup	*50,000*	25,000	25,000
Total Engine-Specific	330,000	305,000	305,000
Amortized over 5 yrs	*84,841*	78,413	78,413
New Machine Tools	0	0	0
Amortized over 10 yrs	0	0	0
Total Fixed Cost/Yr	84,841	78,413	78,413
Annual Production	**1,200,000**	**200,000**	**35,000**
Fixed cost/engine	**0.07**	**0.39**	**2.24**

Table 20: Summary of the variable and fixed costs for improving piston and ring designs for SV engines.

	Case 1	Case 2	Case 3
Total Added Manufacturing Cost	2.73	2.73	2.73
Fixed Costs	0.07	0.39	2.24

4.5 Improvement in Manufacturing Variability[1]

Table 21: Estimated fixed costs for the changes in improving manufacturing variability for SV engines.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (1 year @ $100,000)	100,000	100,000	100,000
Testing costs	60,000	60,000	60,000
Other engineering	25,000	25,000	25,000
Total Engineering	185,000	185,000	185,000
Technical support			
Training/Tech. Pubs	0	0	0
Tooling Costs			
New Master Dies			
None	0	0	0
Total Tooling	0	0	0
Machine Tool Setup	100,000	50,000	50,000
Total Engine-Specific	285,000	235,000	235,000
Amortized over 5 yrs	73,271	60,417	60,417
Add'l Machines and QA	355,000	100,000	38,000
Amortized over 10 yrs	55,316	15,582	5,921
Total Fixed Cost/Yr	128,587	75,999	66,338
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.11**	**0.38**	**1.90**

To meet the proposed emission durability requirement, it will be essential to reduce manufacturing variability by tightening manufacturing tolerances, and by having a good quality control program. To achieve tighter tolerances may require a reduction in throughput, thus requiring additional machines to meet the same production level. More precise assembly operations, and more frequent quality inspection will also slow down the assembly processes, requiring more workers to produce a similar throughput. Additional people and quality control machines and tools would be needed for the QA/QC program. We considered all these requirements in our cost analysis. Since it is based mainly on manufacturing practices and processes, the cost analysis for this improvement is applicable for both the SV and OHV engines.

As shown in Table 21, we estimated that it the reduction in variability would require the efforts of about one engineer (industrial/research) for about one year, which translated to about $100,000. These efforts would go into identifying and correcting the sources of manufacturing variability. The costs of engineering tests to identify the source and consequences of manufacturing variability are estimated at $60,000. Other engineering costs such as special supplies and tools, test materials and so forth are estimated at $25,000. We also estimated that the setup costs to implement these changes in the production process would be about $100,000 for the 1.2 million unit case and 50,000 for the other two cases.

Adding all these costs up, the total engine specific costs are about $285,000 for the high-volume and $235,000 for the two lower-volume cases. Amortizing these estimates over five years at 9%

[1] Note that the improvement in manufacturing variability does not include tightening the manufacturing tolerance for the carburetor. Manufacturing variability for the carburetor is addressed separately in the next section as improved carburetors are assumed to be used in both SV and OHV engines. Therefore, the number of annual production would be different, and hence, the cost estimates would be different.

capital rate, the total engine specific costs are $73,000 for the high-volume case and $60,400 for the two other lower-volume cases.

It would be necessary for the manufacturer to purchase additional machine tools to compensate for the reduction in throughput. We estimated the reduction in throughput at 30%. For the 1.2 million unit case, we estimated that this would require the equivalent of 5 vertical CNC machining centers at $55,000 each, plus about $80,000 in QA/QC equipment. For the 200,000 unit case, we estimated the requirement at 1 CNC machining center plus $45,000 in QA/QC equipment, and for the 35,000 unit case at 1/4 of one CNC machine plus $25,000 in QA/QC equipment. These costs were amortized over ten years at 9%. The total amortized fixed costs amount to $129,000 per year for the 1.2 million unit case, $75,000 per year for the 200,000 unit case, and $66,000 per year for the 35,000 unit case. Dividing these costs by the annual production gives fixed costs per engine of $0.11, $0.38, and $1.90, respectively. These costs would be essentially the same for a class II engine.

We also assumed that it would require one addition skilled labor minute per engine or about $0.35 to perform the QA/QC program. This variable manufacturing cost is shown in the summary table (see Table 22).

Table 22: Summary of the total added manufacturing and fixed costs for improving manufacturing variability for SV and OHV engines.

	Case 1	Case 2	Case 3
Total Added Manufacturing Cost	0.35	0.35	0.35
Fixed Costs	0.11	0.38	1.90

4.6 Improvement in Carburetor

One critical engine part that would especially require tighter manufacturing tolerances is the carburetor. Manufacturing variations in the carburetor directly affect the air-fuel ratio, and thus the engine emissions and performance. The reduction in carburetor variability was not included in the previous section, but is treated separately here. Since the same carburetor model is often used on several different models of engines, carburetor production volumes are considerably higher than those of individual engine models. While some of the largest engine manufacturers make their own carburetors, many engine makers buy their carburetors from specialized suppliers such as Walbro, who are thus able to achieve substantial economies of scale. For this analysis, we assumed that the improved carburetor would be used in both low-volume and high-volume models, and in both SV and OHV engines. Thus, the annual production engines would be much greater than 1.2 million engines. We assumed that these improved carburetors would be used in 4 million engines (see Appendix D for basis).

Similar to the improvement in manufacturing variability, reducing manufacturing tolerances in the carburetor would require reduced machining throughput, increased care in the assembly operation, and frequent quality inspection. As shown in Table 23, we estimated that the reduction in manufacturing variability would require the efforts of about two industrial/research engineers for one year. The costs of testing to establish the causes and effects of manufacturing variability were estimated at $60,000. Other engineering costs such as test engines, travel, test materials and so forth were estimated at $25,000. Changes to the technical documentation for the carburetor were estimate at $20,000.

The cost of a new master die for the die-cast carburetor body was estimated at $60,000, based on a discussion with Walbro engineers. Changes to the assembly line, materials and components handling were estimated at $100,000. Adding all these costs up, the total carburetor model-specific cost is about $465,000. Amortizing these estimates over five years at 9% capital rate, the total model-specific fixed cost is $156,000. In addition to these costs, we assumed that the change to more precise machining processes would require about one million dollars in capital investment. Amortizing this estimate over a ten year period and at a 9% capital rate, the fixed cost for these machines would be about $156,000. Dividing the sum of the fixed costs by the annual production volume, the fixed cost per carburetor is $0.07.

Table 23: Estimated fixed costs to reduce manufacturing variability in carburetors.

	Case 1
Engineering Costs	
Engineering labor + OH (2 year @ $100,000)	200,000
Number of Tests	200
Test Cost ($)	300
Testing costs	60,000
Other engineering	25,000
Total Engineering	285,000
Technical support	
Training/Tech. Pubs	20,000
Tooling Costs	
New Master Dies	
Carburetor	60,000
Total Tooling	60,000
Machine Tool Setup	100,000
Total Model-Specific Costs	465,000
Amortized over 5 yrs	119,548
New Machine and QA/QC	1,000,000
Amortized over 10 yrs	155,820
Total Fixed Cost/Yr	275,368
Annual Production	4,000,000
Fixed cost/engine	**0.07**

We also assumed that it would require one addition skilled labor minute per unit or about $0.35 to perform the QA/QC program. This cost is also reflected in Table 24, which is a summary of total hardware/assembly costs and fixed costs for tightening manufacturer tolerances for the carburetor.

Table 24: Summary of the total added manufacturing and fixed costs for improving carburetor for SV and OHV engines.

	Case 1
Total Added Manufacturing Cost	0.35
Fixed Costs	0.07

5. COST ANALYSES FOR IMPROVING OVERHEAD-VALVE ENGINES

This chapter presents our cost analysis for the improvements in overhead-valve engine technology. OHV technologies improvements considered in this study were the following:

- improvement in combustion and intake systems
- improvement in piston and ring designs, and in bore finish

We assessed both variable and fixed costs three cases: 1.2 million engines per year, 200,000 engines per year, and 35,000 engines per year. The basis for these numbers is discussed in Appendix D.

5.1 Improvement in Combustion and Intake Systems

In general, OHV engines are able to operate at a leaner air/fuel ratio than SV engines due to their better cooling and airflow characteristics. Also the combustion characteristics are generally better than those of SV engines, due to the smaller surface-to-volume ratio in the OHV combustion chamber. However, additional emission reductions may still be realized by operating at an even leaner air/fuel ratio, and by optimizing the combustion chamber geometry and intake airflow characteristics. In order to operate on a lean mixture, it is necessary to have a better prepared mixture by inducing more swirl in the intake manifold, and by designing a better squish area to induce more turbulent flow, and hence, better mixing during combustion.

The incremental costs of improving the combustion and intake systems are essentially due to the fixed costs of research, design and development, and changes in production tooling. As in the case of SV engines, combustion and intake system improvements are not expected to affect variable costs, since they would require only modifications of existing engine parts, and would not add new parts or assembly processes. Examples would include a new combustion chamber with a smaller surface to volume ratio and/or with a squish band, and a change in intake system geometry to induce more swirl in the combustion chamber to improve combustion characteristics. Although changes in part geometry might have some minor impact on material requirements, these impacts are very difficult to predict, and could involve either an increase or a decrease in material. For this analysis, we have assumed no impact on material or assembly labor requirements.

The estimated fixed costs of improving the combustion and intake systems are tabulated in Table 25. We estimated that about two engineer-years would be required to carry out the research, development, and design work involved in improving combustion and intake systems for OHV engines. This is twice the estimate for the SV engines. Since small engine manufacturers have more experience with SV than OHV engines, we assumed that more engineering effort would be required to first convert to OHV and then to improve the OHV engine design.

Extensive emission testing would be required to develop the optimized intake and combustion chamber. This was estimated to require 200 emission tests, at $300 each. Other engineering-related costs such as test engines, prototyping, travel, test materials and so forth were estimated at $25,000. The total engineering costs would then be $285,000. These costs would not be greatly different between any of the engine cases.

The cost of changes to parts lists and other technical documents was estimated at $20,000, or about the cost of two technical bulletins.

Table 25: Estimated fixed costs for the changes in improving combustion chamber and intake systems for OHV engines.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (2 years @ $100,000)	200,000	200,000	200,000
Number of Tests	200	200	200
Test Cost ($)	300	300	300
Testing costs	60,000	60,000	60,000
Other engineering	25,000	25,000	25,000
Total Engineering	285,000	285,000	285,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
New Master Dies			
Cylinder head	60,000	60,000	60,000
Piston	25,000	25,000	25,000
Total Tooling	85,000	85,000	85,000
Machine Tool Setup	50,000	25,000	25,000
Total Engine-Specific	440,000	415,000	415,000
Amortized over 5 yrs	113,121	106,693	106,693
New Machine Tool	0	0	0
Amortized over 10 yrs	0	0	0
Total Fixed Cost/Yr	113,121	106,693	106,693
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.09**	**0.53**	**3.05**

Tooling costs to implement the geometric changes would include the costs of new master dies for the cylinder head and piston. The costs for the cylinder head and piston master dies for an OHV engine are estimated at $60,000 and $25,000, respectively, based on our conversations with die makers (Spec Cast, Prince Machine and Muller Weingaren, 1996). The costs of the necessary changes in the production process, jigs, transfer equipment, etc. are estimated at $50,000 and $25,000 for the high-volume and the two lower-volume cases, respectively. Thus, the total engine-specific costs are estimated at $440,000 for the 1.2 million unit case, and $415,000 for the 200,000 and 35,000 unit cases. These costs were amortized over five years at a cost of capital of 9%. No new machine tools would be needed, so the total amortized fixed costs amount to $113,000 per year for the 1.2 million unit case and $107,000 per year for the other two. Dividing by the number of units produced results in fixed costs of $0.09 per engine for the 1.2 million unit case, $0.53 per engine for the 200,000 unit case, and $3.05 per unit for the 35,000 unit case.

5.2 Improvement in Piston and Ring Designs and Bore Smoothness

Table 26: Estimation of incremental variable manufacturing cost for improving piston and ring designs for OHV engines.

	Cost/ Piece	Pieces/ Engine	Total
Piston	1.75	1	1.75
Piston Rings	0.50	1	0.50
Total Added Variable Manufacturing Cost			2.25

In OHV engines, as in SV engines, it may be necessary to reduce the amount of lubricating oil that enters the combustion chamber in order to reduce the formation of carbon deposits. These deposits increase HC emissions and degrade combustion. This may require improvements in the design of the piston and piston rings (note that OHV engines already have valve stem seals on both the intake and exhaust valves, so that these would not constitute an added cost). Improvements in the roundness and finish of the cylinder bore may also be needed. According to one engine manufacturer we consulted (Briggs and Stratton, 1996), the development effort to produce a better piston and ring package for an OHV engine would be similar to that for an SV engine. For our cost analysis, we assumed that permanent-mold cast pistons and better ring package would be required to improve the piston and ring designs. The pistons were assumed to be obtained from an outside supplier, at an additional cost of $1.75. The additional cost of the better quality ring package was estimated at $0.50 (Table 26).

The estimated fixed costs for the piston and ring improvements in the OHV case are similar to those estimated for the SV case, which were documented in Table 19. The main differences are that we assumed an investment in new machine tools due to reduced throughput in the cylinder boring process resulting from the need for improved bore roundness and finish. For the 1.2 million unit case, this was estimated to require the equivalent of four new boring machines at $100,000 each. For the 200,000 unit case, one boring machine was assumed, and 1/4 of a boring machine for the 35,000 unit case. The resulting cost estimates are shown in Table 27. Table 28 shows a summary of the hardware/assembly costs and fixed costs for improving piston and ring designs, and improving bore finish for OHV engines for the three cases.

Table 27: Estimated fixed cos. for the changes in improving pist.n and ring designs for .HV engines.

	Case 1	Case 2	Case 3
Engineering Costs			
Engineering labor + OH (2 years @ $100,000)	100,000	100,000	100,000
Emission Testing	30,000	30,000	30,000
Durability Testing	100,000	100,000	100,000
Testing costs	130,000	130,000	130,000
Other engineering	15,000	15,000	15,000
Total Engineering	245,000	245,000	245,000
Technical support			
Training/Tech. Pubs	20,000	20,000	20,000
Tooling Costs			
New Master Dies			
Connecting Rod	15,000	15,000	15,000
Total Tooling	15,000	15,000	15,000
Machine Tool Setup	50,000	25,000	25,000
Total Engine-Specific	330,000	305,000	305,000
Amortized over 5 yrs	84,841	78,413	78,413
New Machine Tool	400,000	100,000	25,000
Amortized over 10 yrs	62,328	15,582	3,896
Total Fixed Cost/Yr	147,169	93,995	82,309
Annual Production	1,200,000	200,000	35,000
Fixed cost/engine	**0.12**	**0.47**	**2.35**

Table 28: Summary of the variable and fixed costs for improving piston and ring designs for OHV engines.

	Case 1	Case 2	Case 3
Total Added Manufacturing Cost	2.25	2.25	2.25
Fixed Costs	0.12	0.47	2.35

PART II

BOTTOM UP COST ANALYSIS FOR HANDHELD EQUIPMENT ENGINES

6. HANDHELD ENGINES

Except for battery-electric or cord-electric equipment, nearly all small engines used in handheld equipment (e.g., chainsaw, trimmers) use the crankcase-scavenged two-stroke design. Additionally, a four-stroke handheld engine, used in trimmer equipment, has been developed and is now on the market. The distinction between two-stroke and four-stroke small engines is an important one for emissions, as two-stroke engines tend to emit much greater amounts of unburned hydrocarbons (HC) and particulate matter (PM) than four-stroke engines of similar size and power. The high PM emissions are due to the fact that lubricating oil is mixed with fuel in two-stroke engines. Two-stroke engines also display markedly poorer fuel economy than four-strokes, but tend to have higher power output, quicker acceleration, and lower manufacturing costs. Because of their advantages in performance and manufacturing cost, two-stroke engines are used extensively in small equipment where this is permitted by emission regulations.

The reasons for using two-stroke engines include compactness and the ability to operate in a variety of positions, including upside down, as well as better power-to-weight ratio and lower manufacturing cost. These engines range from 20 to 100 cc displacement. Recently, a handheld engine and equipment manufacturer, Ryobi, has introduced string trimmers powered by a four-stroke engine with overhead-valves. The Ryobi four-stroke engine is discussed later in the chapter. Recently, Honda also announced that it will introduce a small four-stroke engine for applications in handheld equipment, but details of this engine are not yet available.

The operating principles, emission characteristics, and emission control technologies for small four-stroke engines were discussed in Chapter 2. This chapter discusses the general operating principles, emission characteristics, and emission control technologies for two-stroke engines, and for lightweight four-stroke engines suitable for handheld use.

6.1 Operating Principles of Small Two-Stroke Engines

A two-stroke small engine can be much simpler mechanically than a four-stroke engine. The operating principles are very simple as well. Blair (1990) provides an excellent and very thorough discussion of two-stroke engine design and operation. Four stages in the combustion cycle of a simplified two-stroke engine are shown in Figure 11. In the first stage (Figure 11a), near the top of the compression stroke, the compressed charge in the cylinder is about to be ignited by the spark plug. At the same time the partial vacuum created by the rising piston draws fresh air-fuel mixture into the crankcase. Ignition is followed by combustion, and the pressure of the hot burned gases forces the piston down. As the piston approaches the bottom of the cylinder, the exhaust port in the wall of the cylinder is uncovered, and the combustion gases "blow down" into the exhaust port (Figure 11b).

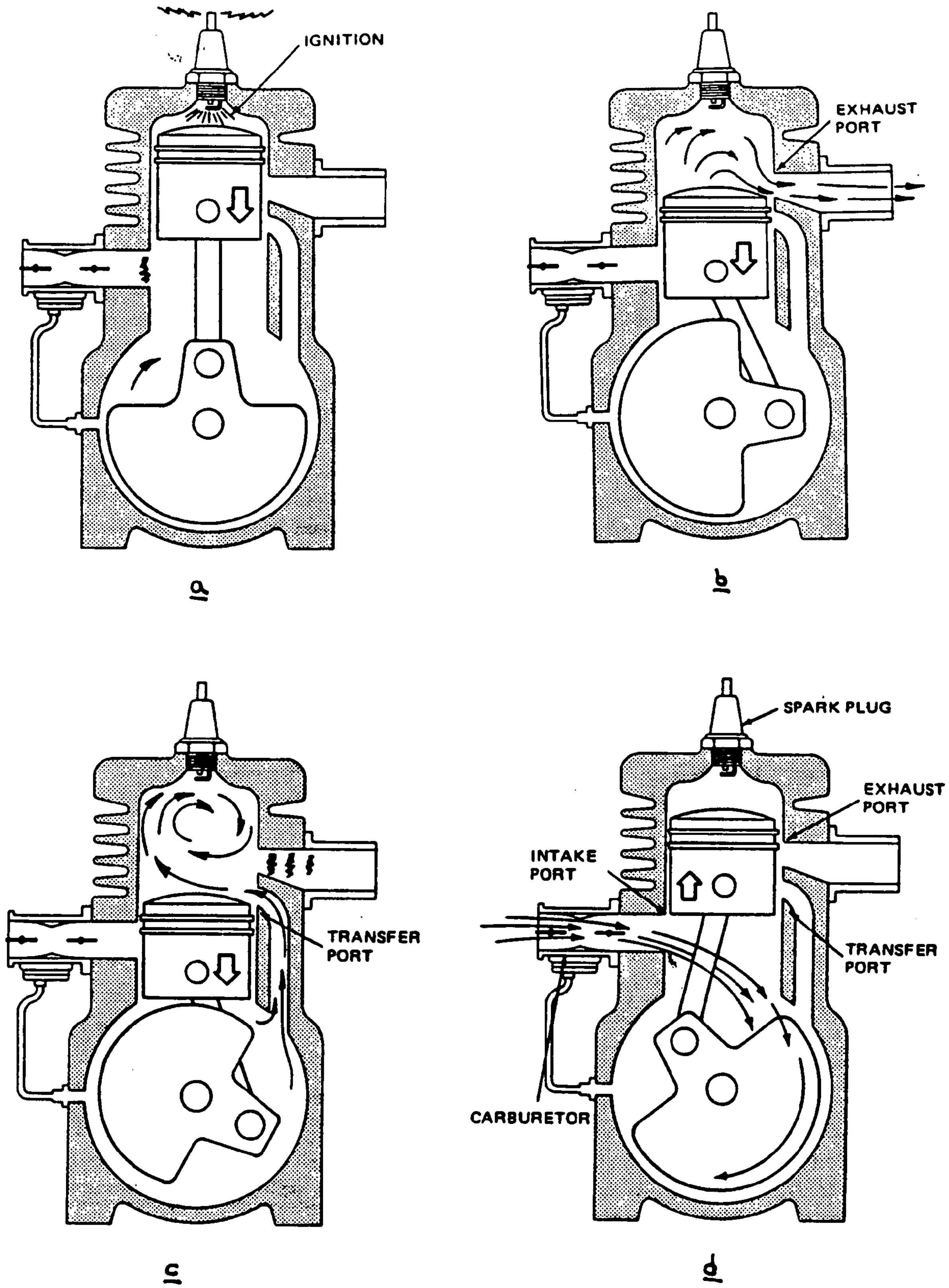


Figure 11: Operation of a two-stroke, loop scavenged engine.

As the piston gets closer to the bottom of its stroke, the transfer ports are uncovered, and air-fuel mixture from the crankcase is forced into the cylinder (Figure 11c). The pumping force required to move the air-fuel mixture is provided by the downward motion of the piston. Since the exhaust port is still open, the burned gases are pushed from the cylinder by the pressure of the incoming charge. In the process, however, some mixing between the exhaust gas and the charge takes place, so that some of the exhaust is retained in the cylinder, and some of the fresh charge is emitted in the exhaust. As the piston again rises for the next compression stroke, it closes first the transfer port and second the exhaust port - trapping the remaining charge in the cylinder. Before the exhaust port closes, however, the rising piston pushes some of the charge in the cylinder out into the exhaust (Figure 11d).

Since the gas exchange processes in a two-stroke engine are controlled by its piston and ports, the complex valve gear, camshaft, and related mechanisms needed in a four-stroke engine are not needed. For this reason, two-stroke engines are easier and cheaper to manufacture than four-stroke engines.

6.2 Causes of Emissions from Two-Stroke Engines

In small two-stroke engines, the major sources of unburned hydrocarbon emissions are the loss of unburned charge out the exhaust ports during scavenging, and hydrocarbon emissions due to misfire or partial combustion at light loads. The fraction of the total charge fed to the cylinder that is trapped to participate in the combustion process is known as the "trapping efficiency". At full load, trapping efficiency for a chainsaw engine may be as low as 55% (Blair, 1990) - implying that 45% of the fuel-air mixture supplied to the engine is emitted unburned in the exhaust (Hare et al, 1974; Batoni, 1978; Nuti and Martorano, 1985).

Under light-load conditions such as idle, the flow of fresh charge is reduced, which increases the trapping efficiency. However, scavenging efficiency is also reduced, allowing substantial amounts of exhaust gas to be retained in the cylinder. This high fraction of residual gas can cause incomplete combustion or misfire. Misfiring or incomplete combustion cycles are the source of the "popping" sound commonly produced by two-stroke engines at idle and light loads, as well as the problems that these engines often have in maintaining stable idle. These unstable combustion phenomena are major sources of HC emissions under idle and light-load conditions (Tsuchiya et al, 1983; Abraham and Prakash, 1992; Aoyama et al, 1977).

Another source of the high HC and CO emissions typical of two-stroke engines is the air-fuel ratio, which is normally set very rich compared to (e.g.) four-stroke automotive engines. For conventional carburetted two-stroke chainsaw engines, the mixture is usually set around 12:1 by weight, compared to a stoichiometric air-fuel ratio of 14.7:1. This increases the maximum power output from the engine, and helps to limit the engine temperature, as well as providing easier starting. Since there is insufficient oxygen present in the cylinder to fully burn all the fuel to CO_2, however, substantial amounts of CO and HC are emitted in the exhaust.

The source of the high level of particulate emissions characteristic of two-stroke engines is the lubricating oil that is added to the fuel to lubricate the crankcase parts. Since the crankcase is used as a pump, it cannot contain a pool of oil to lubricate the bearings as well. Thus, lubricating oil is mixed into the fuel instead. When the fuel is atomized in the carburetor and vaporizes, the less-volatile oil is left as a mist of oil droplets in the air-fuel mixture. Some of these droplets contact the cylinder walls, the crankshaft bearings, and other parts that require lubrication. Most of the oil, however, is carried into the combustion chamber along with the air-fuel mixture. The oil in that part of the air-fuel mixture that is not trapped and burned appears as particulate matter in the exhaust. Even the oil that is trapped often fails to burn completely. The presence of condensed oil droplets in the exhaust is responsible for the two-stroke's characteristic white or blue smoke emissions.

Since two-stroke SI engines usually retain significant exhaust gas in the cylinder and run at rich air-fuel ratios, flame temperature and NOx concentrations are usually low. Measures to reduce CO and HC emissions from two-strokes, to the extent that they result in leaner air-fuel ratios, are likely to increase NOx emissions.

6.3 Emission Levels for Handheld Two-Stroke Engines Meeting EPA Phase 1 Emission Standards

Since engine emissions have only recently been regulated, emission data are scarce, and are generally available only for new engines in proper running condition. The limited data available are presented in this section.

Figure 12 shows emissions certification data for California 1995 model handheld utility equipment engines. These engines were certified to California Tier I standards, which are similar to EPA's Phase 1 emission standards. The average emission levels for these certified engines are shown in Table 29.

An interesting observation on the emission data in Figure 12 is that the emissions for the only engine with displacement greater than 50 cc were quite low. These data were for a 56 cc blower engine manufactured by Stihl. Discussions with a Stihl engineer revealed that the blower engine is designed to run leaner than other engines. This engine can afford to run leaner without fear of overheating, since the blower provides a very high flow of cooling air.

To meet the EPA Phase 1 or the California Tier I standards, most handheld equipment engines required enleanment in fuel/air mixture, improvements in fuel metering, changes in ignition timing, and improved cooling. Some engines required minor design changes as well. To achieve additional reductions in HC and CO emissions, small two-stroke engines may require advanced engine modifications and/or use of aftertreatment devices.

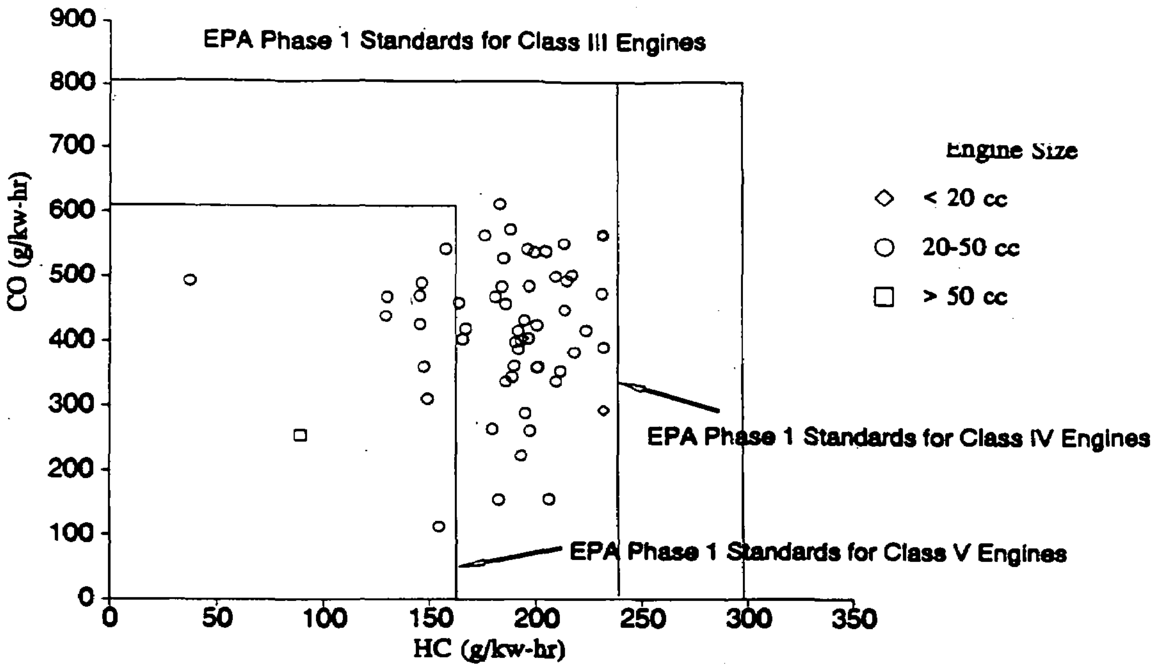


Figure 12: CARB 1995 certification data compared to EPA Phase 1 handheld engine standards.

Table 29: Average emission levels for handheld equipment engines that meet EPA Phase 1 and CARB Tier I standards.

Eng. Disp. (cc)	THC (g/Kw-hr)	CO (g/Kw-hr)	NOx (g/Kw-hr)
Engine Displacement: < 20 cc			
18.0	220	422	1.1
Engine Displacement: 20 - 50 cc			
31.8	186	418	1.6
Engine Displacement: > 50 cc			
56.0	89	254.7	3.55

6.4 Emission Control Technologies for Small Two-Stroke Engines

Compared to small non-handheld engines, small handheld engines pose even more difficult problems for emission control. These handheld engines are frequently used in situations that demand multi-position capability, which may not currently be conducive to certain engine modification technologies (e.g., four-stroke handheld). The engines must remain lightweight, therefore certain weight intensive emission controls would not be feasible. Additionally, the contact proximity of the handheld engine to the operator poses issues for heat generation using certain technologies (e.g., catalytic converters). Also, the tolerances for the two-stroke have to be more exact and there is generally less flexibility in redesign of the handheld versus the non-handheld small engine.

Technologies potentially applicable to reducing small two-stroke engine emissions can be grouped into the following categories:

- improved scavenging characteristics;
- combustion chamber modifications;
- improved ignition systems;
- exhaust aftertreatment technologies;
- conversion to four-stroke engines;
- improvements in engine lubrication; and
- advanced fuel metering systems.

The application of some of these technologies to small engines to reduce exhaust emissions have been reported in a number of studies, and there is now significant practical experience with some of these techniques. The emission control technologies that are within the scope of this study – scavenging control, stratified scavenging, improvements in the combustion chamber, improvement in spark ignition, exhaust aftertreatment, and conversion to four-stroke – are discussed below. Other technologies are presented in Appendix C.

Scavenging Control Technologies

In a two-stroke engine, the exhaust and intake events overlap extensively, as the piston finishes its downward stroke and begins its movement from the bottom of the cylinder to the top. As the piston approaches the bottom of the cylinder, exhaust ports in the walls of the cylinder are uncovered. When this happens, the high pressure combustion gases blow out through the exhaust port. As the piston gets closer to the bottom of its stroke, the intake ports are opened and fresh air or air-fuel mixture is blown into the cylinder while the exhaust ports are still open. Piston movement timing (measured in crank angle) and cylinder port configuration are the major factors controlling the scavenging process. The ideal situation would be to retain all of the fresh charge in the cylinder (high trapping efficiency) while exhausting all of the spent charge from the last cycle (high scavenging efficiency). These two goals conflict. In production engines, the cylinder ports and timing are generally designed for high scavenging efficiency, in order to achieve maximum power output and smoother idle, at the expense of higher short-circuiting losses and HC emissions. It is possible to reconfigure the intake and exhaust ports to fine-tune the scavenging characteristics for lower emissions, but this involves significant trade-offs with engine performance. Another way to increase trapping efficiency, with minimum impact on performance, is to apply exhaust charge control technology.

Exhaust charge control technology modifies the exhaust flow by introducing one-way control valves in the exhaust, or by making use of the exhaust pressure pulse wave. Using the exhaust pressure pulse wave to control intake and exhaust flow usually requires a fairly long exhaust pipe, and is effective only for a restricted range of engine RPM. For this reason, one-way control valves are usually used to control the exhaust flow rate in small engines. The critical variable parameter for exhaust charge control techniques is the contraction ratio, which is defined as the ratio of the restricted exhaust passage area regulated by the valve to the unrestricted exhaust passage area. The effectiveness of these techniques is measured by the delivery ratio, which is the ratio between the mass of air-fuel mixture actually delivered to the engine and the mass of air-fuel mixture contained by the engine displacement volume at ambient conditions.

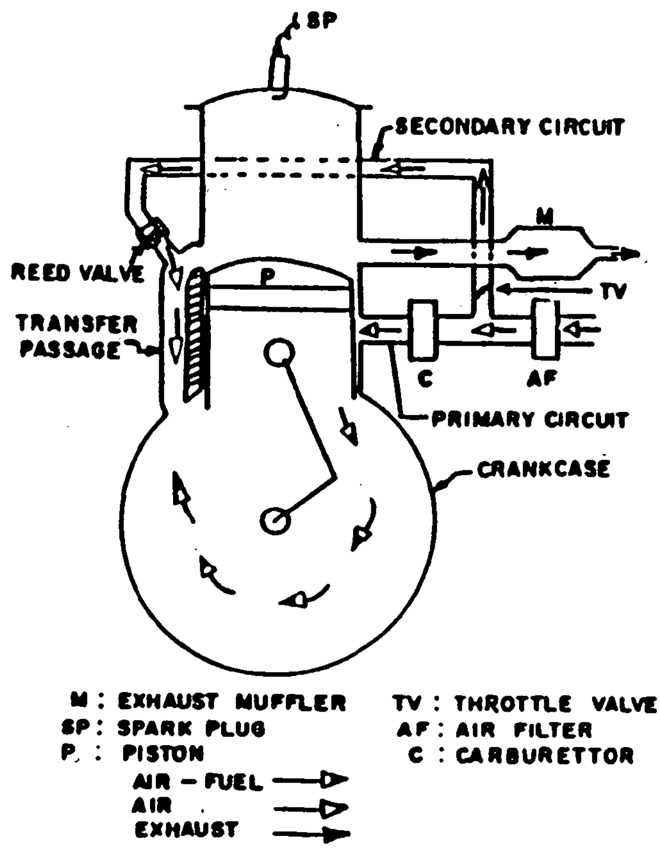


Figure 13: Schematic to illustrate the stratified scavenging approach in a two-stroke engine.

Stratified Scavenging

Stratifying the charge in a two-stroke engine can reduce scavenging losses and HC emissions. One stratified scavenging approach is shown in Figure 13. In this approach, a supply of pure air is first introduced into the cylinder during the start of the scavenging process, to displace the exhaust gas, and is then followed later by a rich fuel/air mixture to support combustion. Controlled by reed valves, the secondary air supply can be inducted either through transfer passages or through the crankcase. The simplest approach is to pre-fill the transfer passages between the crankcase and combustion chamber with pure air, inducted separately from the air-fuel mixture entering the crankcase.

Ideally, with stratified scavenging, most of the charge lost from the cylinder will be pure air or a very lean air-fuel mixture. Thus, scavenging losses are minimized. However, it is impossible to obtain a perfect "two-layer" charge (pure air, and rich fuel/air mixture), while accurately supplying the right amount of pure air to effectively displace the exhaust gas during the actual scavenging process at different load/speed conditions. Thus, there will still be some fresh fuel/air charge scavenged out the exhaust port(s) with the stratified scavenging approach. A number of researchers have tested different designs based on the stratified scavenging concept, and their designs are discussed in Appendix C.

Improvements in the Combustion Chamber

Combustion chamber and piston configurations can be improved to induce more turbulent motion to improve mixing during the compression stroke, as well as to control the flow direction of the fresh charge to minimize losses due to unburned fuel. Using improved combustion chamber and piston configurations with more swirl and squish can also minimize the formation of pocket or dead zones in the cylinder volume where burned gases can become trapped and escape displacement or entrainment by the fresh scavenging flow. Laimbock et al. of Graz University of Technology (GUT) in Austria have designed a "jockey-cap" shape like combustion chamber which concentrates the squish area only above the exhaust port (Laimbock and Landerl, 1990). This "jockey-cap" type combustion chamber is designed to force the fresh charge to flow over the spark plug, which improves the cooling and allows the engine to run leaner without pre-ignition.

Recently, Kawasaki modified the combustion chamber of a 25 cc chainsaw engine to increase the power output to overcome the power loss due to retarding the exhaust timing for HC and NOx emission reductions (Tamba S. et al, 1995). A 48% HC emission reduction and 85% CO emission reduction were achieved through enleanment and retarding exhaust timing. Some other minor modifications, such as combustion chamber and exhaust port modifications, and improved cooling, were also incorporated to overcome engine and exhaust gas temperature rise due to the leaner mixture, and power loss problems. The Kawasaki study showed that there is still a lot of room for engine modifications for small engines to reduce emissions.

Improvement in Spark Ignition and Timing

The effect of ignition timing on two-stroke engines is essentially the same as on four-stroke engines. Retarding ignition timing beyond the minimum for best torque (MBT) point reduces power and increases fuel consumption, but reduces NOx and (within limits) HC emissions. Retarding ignition timing, especially at high loads, may offer a means of recovering much of the increase in NOx emissions that will otherwise result from using a leaner mixture in low-emission two-stroke engines. Advancing ignition timing at light load reduces HC emissions in direct fuel-injected engines by reducing the dispersion of the fuel cloud. The cloud is therefore less likely to contact the walls of the combustion chamber. This reduces the amount of unburned HC produced by the quenching effect at the combustion chamber walls, as well as the filling of crevice volumes with unburned mixture. The unburned HC due to flame quenching and crevice volumes are major sources of HC exhaust emissions. With better combustion quality at advanced ignition timing, CO emissions are also reduced. NOx emissions, however, are increased with advanced ignition timing.

Researchers at ITRI have used a dual spark plug ignition in a scooter two-stroke engine to determine the effects on engine torque and unburned HC emissions (Huang et al, 1991). It was reported that the engine with dual spark plugs yielded lower HC emissions and better engine torque at low and medium engine load conditions. The improvements were believed to be due to the increase in combustion speed and the decrease in mixture bulk quenching effect when the dual plug ignition was used. However, ITRI's findings also showed that using additional spark plugs did not improve the high unburned HC emissions under idling or light-load conditions.

Exhaust Aftertreatment Technologies

The use of aftertreatment technologies such as thermal oxidation and catalytic converters can provide additional control of emissions beyond that achievable with engine and fuel-metering technologies alone. Catalytic converters have been demonstrated on a limited basis in small two-stroke engines.

Thermal Oxidation - Thermal oxidation is used to reduce emissions of HC and CO by promoting further oxidation of these species in the exhaust. This further oxidation usually takes place in the exhaust port or pipe, and may require the injection of additional air to supply the needed oxygen. Substantial reductions in HC and CO emissions can be achieved through thermal oxidation if the exhaust can be maintained at a high enough temperature long enough. The typical temperature levels required for HC and CO oxidation are about 600 and 700 °C respectively. Although these requirements are difficult to meet for small engines with typical short exhaust systems, the technique has been demonstrated in a modified small four-stroke engine by introducing secondary air into the stock exhaust manifold upstream of the engine muffler. Air injection at low rates into the stock exhaust system was found to reduce emissions by as much as 77% for HC and 64% for CO (White et al, 1991). However, this was effective only under high-power operating conditions. In addition, the high exhaust temperatures required to achieve this oxidation would substantially increase the skin temperature of the exhaust pipe.

Oxidation Catalyst - Like thermal oxidation, the oxidation catalyst is used to promote further oxidation of HC and CO emissions in the exhaust stream, and it also requires sufficient oxygen for the reaction to take place. Some of the requirements for a catalytic converter to be used in two-stroke engines include high HC conversion efficiency, resistance to thermal damage, resistance to poisoning by sulfur and phosphorus compounds in the lubricating oil, and low light-off temperature. Additional requirements for catalysts to be used in two-stroke engines include extreme vibration resistance, compactness, and light weight.

Catalytic converters available for small engines use either metal or ceramic substrates. Although metal substrates have many advantages - especially resistance to vibration and shock -they are considerably more expensive. "Ballpark" pricing data from industry sources suggest that a catalytic converter based on a ceramic substrate should cost the engine manufacturer about five dollars per unit, while the cost of a metal substrate would be about four times as high. Although most available test data are on metal substrate catalysts, ceramic substrate suppliers have developed mounting techniques which they believe will allow catalytic converters using these substrates to give durability and performance similar to those of the metal substrate units. Recently, Corning and Engelhard have presented results indicating that the durability requirements of two-stroke engine can be met with the ceramic catalyst substrates with improved mounting systems (Reddy et al., 1995).

Application of catalytic converters to two-stroke engines presents a problem, because of the high concentrations of HC and CO in their exhaust. If combined with sufficient air, these high pollutant concentrations result in catalyst temperatures that can easily exceed the temperature limits of the catalyst. These high temperatures also pose a hazard of fire or personal injury to equipment users. Temperature limits for catalytic converters are similar for metal substrate and ceramic substrate catalysts - both begin to suffer damage at about 1000 °C. Thus, application of catalytic converters to two-stroke engines requires either limiting the air supply to limit pollutant oxidation and the resulting exotherm, or engine modifications to reduce the concentration of pollutants in the exhaust before the catalyst.

A number of researchers have applied oxidation catalytic converters to small two-stroke engines. Researchers at Graz University of Technology, ITRI in Taiwan and several other organizations have all published data on the application of catalytic converters in small two-stroke engines (Mooney et al., 1975; Engler et al., 1989; Burrahm et al., 1991; Laimbock and Landerl, 1990; Laimbock 1991; Hsien et al, 1992; Pfeifer et al., 1993; Gulati et al., 1993; Castagna et al., 1993). Some of these studies are discussed in Appendix C.

As a result of this research, catalytic converters have been used on commercial production two-stroke motorcycles and mopeds in order to meet emissions standards in Taiwan, Switzerland, and Austria. Experience with these systems in consumer use has shown them to be acceptable, except that special heat shielding is necessary to protect the passengers from contact with the catalyst housing, which can have a skin temperature exceeding 500 °C. In Europe, catalytic converters have also been available since 1989 on production model chainsaws - with the primary intention to reduce inhalation of hydrocarbon emissions by the operators. These are presently an expensive option, found mostly on professional saws.

<u>Stihl Production Chainsaws Equipped with Catalytic Converters</u> - Stihl is selling three models of chainsaws equipped with catalytic converters. The engine sizes of these chainsaws range from 49 to 77 cc. The average weight increase for these catalyst chainsaws ranges from 0.44 to 0.66 lbs (0.2-0.3 kg). Emission results obtained from Stihl for a 70 cc chainsaw with enleanment (air-

fuel ratio of 16:1) and catalytic converter showed HC emissions reduced by 85% (from 114 to 13.4 g/kW-hr), and CO emissions reduced by 45% (from 590 to 255 g/kW-hr). However, even with heat shields and mixing ambient air with exhaust, Stihl reported that the maximum exhaust gas stream and skin temperatures were 530 and 300°C, respectively. These temperatures exceeded the US Forest Service's allowable temperature limits, which are 246°C for exhaust gas temperature and 289°C for skin temperature. In addition, these catalytic converters add about $100 to the price of the chainsaw. The added cost is said to be due to the costs for the catalytic element and its support, additional heat resistant material for the muffler, additional structural material for cooling and redirecting hot gases, and development and tooling costs. These latter probably account for the largest share of the increase, due to the very small volume of units over which they are spread.

Husqvarna "E-Tech" Two-Stroke Engines with Catalytic Converters - Recently, Husqvarna has issued several press releases on its "advanced two-Stroke engine", so called "E-Tech" engines, to be used in trimmers. This engine will be used in conjunction with a "lower-temperature" catalytic converter. Husqvarna claims that the E-Tech engine have the potential to reduce combined HC+NOx emissions by 60% compared to EPA Phase 1 standards. Husqvarna indicates that these reductions are achieved by means of a better scavenging process and the use of a catalytic converter. However, as of today, no emission data were publicly available for this engine.

Other Catalyst Research on Two-Stroke Engines - United Emission Catalyst (UEC) has investigated the use of catalysts in leaf blowers to determine the maximum reduction of HC and CO emissions possible using a catalyst size limited to that which will fit in a standard muffler housing (Hobbs, 1995). A leaf blower engine was tested with and without catalyst at idle and WOT conditions. Emission results with a 64 cell catalyst showed 58% and 50% reduction in HC emissions at idle and WOT conditions, respectively. The CO emissions were reduced by 25% at idle and 49% at WOT conditions. However, the exhaust outlet temperature was increased from 95 to 145°C at idle, and 250 to 370 °C at WOT.

Pfeifer et al. (1993) also studied the effects of catalytic converters on exhaust HC, smoke and PM emissions for two-stroke motorcycle engines. The results showed that the catalytic converter not only reduced HC emissions, but PM emissions as well. Thus, the use of catalytic converters on two-stroke engines will significantly reduce PM emissions and smoke as well as HC and CO emissions.

Additional catalytic converter developments are described in Appendix C.

Conversion to Four-Stroke Engines

As discussed previously, four-stroke engines inherently produce less HC, CO, and particulate emissions than two-stroke engines. Therefore, one way to reduce emissions from small equipment using two-stroke engines is to convert the equipment to use four-stroke engines if the applications of the equipment permit. In California, nearly all of the two-stroke engines used in non-handheld equipment were replaced by four-stroke designs after the CARB Tier I emission regulations took effect, and the same is expected to occur in the rest of the U.S. when EPA's Phase 1 standards become effective. However, in order to use four-stroke engines in handheld equipment, the engine has to match the performance advantages of a two-stroke engine. These include high power to weight ratio, compactness, and multiposition operating ability. Since four-stroke engines have more mechanical parts, the cost to produce them is higher. In order to be competitive, the cost of the four-stroke engine would need to be comparable to or less than that of the advanced or improved two-stroke engines that could also meet possible Phase 2 standards.

Ryobi Four-Stroke Engine - Ryobi has certified a string trimmer powered by a four-stroke engine to meet CARB Tier I emission standards. This innovative 26 cc four-stroke engine, which uses overhead-valve and exhaust gas recirculation (EGR) technologies, was the result of many years of research and development work within Ryobi. The engine is rated at 0.75 to 1 hp, and has an expected life of about 100 to 200 hours. Ryobi also reports that it can build handheld four-stroke engines up to 3 horsepower. Recently, Honda announced that it will offer a small four-stroke engine for handheld equipment in 1997. However, no detailed information was given regarding the engine.

Emission Levels - The Ryobi four-stroke engine is the first and only handheld four-stroke gasoline engine certified by CARB to meet the Tier I emission standard. The certified emission data are 493 g/kW-hr for CO, 37.5 g/kW-hr for HC, and 4.0 g/kW-hr for Nox emissions. The HC and CO values were determined with the carburetor set in the rich/rich position, and the NOx value was determined with the carburetor set in the lean/lean position.

Ryobi is continuing to refine the engine by limiting carburetor adjustments, as well as using different cam designs and valve timing to control NOx emissions without EGR. The reason for investigating other means to control NOx emissions is that reports indicate the EGR passage in the engine might plug when the carburetor is set at the rich/rich position.

Ryobi also tested the four-stroke engine with a catalytic converter. The results showed that HC, CO and NOx emissions were reduced further. A substantial reduction in NOx emissions was observed (from 4.2 to 0.7 g/kW-hr). However, as with other research on catalytic converters for two-stroke engines, the skin and exhaust temperatures were increased and exceeded the US Forest Service limits. All these results indicate that more testing is necessary with different emission control approaches to reduce the CO emissions while maintaining the NOx emissions or vice versa.

Cost and Weight - Compared to a similar 31 cc two-stroke model that Ryobi offers, the four-stroke string trimmer costs about 50 to 80% more at retail, depending on the design features, and it weighs about 2 to 3 lbs more based on the same specifications. Ryobi also reported that the differential weight can be reduced to less than 0.6 lbs by retooling some injection molded and die cast components.

Engine Features - Ryobi has incorporated many features to reduce the weight and parts in this engine, which in turn make it more compact and less expensive to produce. The innovative design of the cylinder head assembly, which includes the miniature overhead-valve train and EGR passage, allows it to tolerate high speeds and loads. Many of the valve train parts, including the intake and exhaust valves and followers, are interchangeable to reduce manufacturing and inventory costs. A simple gear-lobe-follower assembly is used to control the valve timing instead of the typical two-lobe camshaft used in many engines with overhead-valve configurations.

A small passage is drilled between the intake and exhaust ports to provide EGR. An accelerator pump is also used in this engine to keep the carburetor from going too lean during acceleration. The engine uses the splash lubrication method to lubricate the crankshaft bearing, piston/cylinder and valve train assembly. While Ryobi tried to design the current string trimmer to have multiposition operating ability, field tests have shown that the engine begins smoking and oil drips from the air filter when the trimmer is operated for a few minutes with the exhaust side down. However, the string trimmers do come with a split boom design, which allows the operator to adjust the front part of the trimmer to perform edging while still keeping the engine upright.

Current Status - Ryobi has indicated that it is ready and willing to license its four-stroke engine design to other manufacturers. It has been reported that Ryobi is involved in licensing discussions with several manufacturers, and at least one company is buying Ryobi four-stroke trimmers to be sold under its own brand name.

With Ryobi's demonstration of the feasibility of using small four-stroke engines on string trimmers, many handheld engine and equipment manufacturers are believed to be considering four-stroke engine technology as one of their research and development alternatives to produce low emission handheld equipment, at least for those applications that do not require total multiposition operating ability. These applications include string trimmers and blowers, but not chainsaws. Small four-stroke engine technology is well developed and understood in motorcycle and non-handheld equipment applications. Thus, it will not be surprising to see other four-stroke engines emerging for handheld equipment as one of the viable technologies to meet the emission regulations.

7. COST ANALYSIS FOR CONVERTING TWO-STROKE TO FOUR-STROKE ENGINES

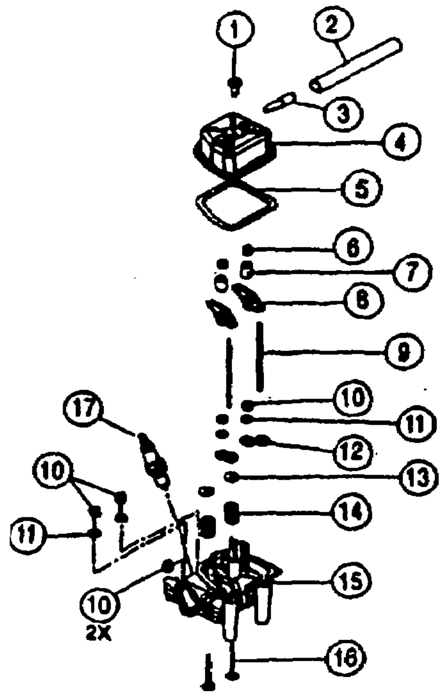
This chapter presents the cost analysis for converting two-stroke engines used in handheld equipment to four-stroke engines. This includes estimates of the incremental variable manufacturing costs (e.g. materials and assembly labor) and fixed costs (e.g. tooling and engineering design) due to the change from two-stroke to four-stroke engines. Since the fixed costs per engine are strongly affected by the production volume, cost estimates were developed for two cases: one with a production volume of 400,000 units annually, and the other with a production of 90,000 units. The basis for selecting these production levels is given in Section 7.2.

7.1 Comparison of Two-stroke and Four-stroke Engines

As discussed in Chapter 6, four-stroke engines tend to have more engine parts than two-stroke engines, due to the need for a valve train assembly to control the flow of air/fuel mixture into the combustion chamber and the flow of exhaust gases out of the chamber. In two-stroke engines, these functions are accomplished by the piston covering and uncovering ports in the cylinder wall. The valve train assembly adds substantially to the parts count, as well as to the weight of the engine. In order to estimate the incremental cost of converting two-stroke engines to four-stroke engines, it was necessary first to characterize the differences between them. Using data developed in a previous study (Chan and Weaver, 1996), we were able to determine the number of additional parts, the difference in material requirements, and the differences in machining operations used to produce each part for a small four-stroke engine and a small two-stroke engine.

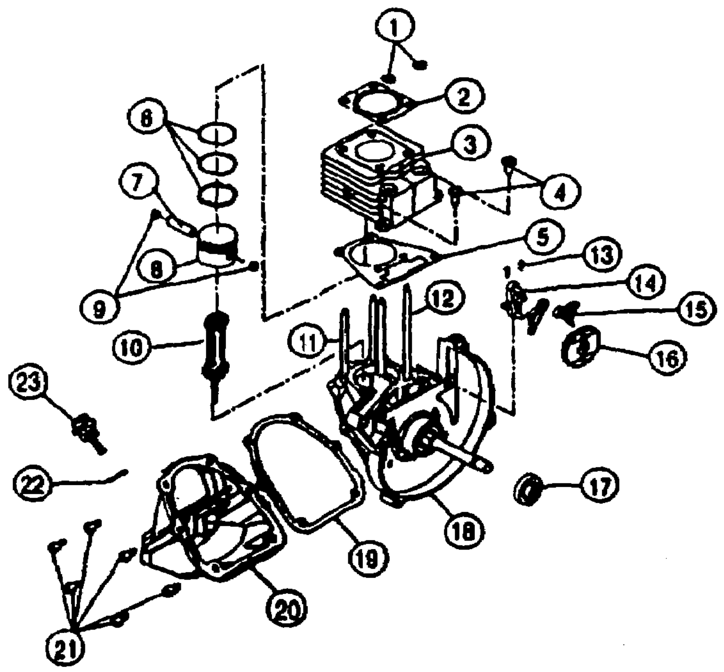
The four-stroke engine that we investigated was the one used in the Ryobi Model 920 string trimmer. The Ryobi engine is the only production four-stroke engine that is presently used in handheld equipment. The two-stroke engine that we used for comparison was the one in the Ryobi Model 720 string trimmer. Exploded views of these engines are shown in Figure 14 and Figure 15, respectively. The parts lists for these engines were also obtained from a distributor, and are included in Appendix B.

Recently, Conley et al. (1996-1, 1996-2, 1996-3) have published three papers on the research, design and development, as well as the emission and performance characteristics, of the Ryobi four-stroke engine. The information in these papers was also used in our cost analysis, along with the data we developed.



Item	Part No.	Description
1	181025	Screw, Valve Cover
2	181026	Hose, Breather
3	181027	Breather Assembly
4	181028	Cover, Valve
5	181029	Gasket, Valve Cover
6	181030	Nut, Rocker Adjusting
7	181031	Pivot, Rocker Arm
8	181032	Arm, Rocker
9	181033	Rod, Push
10	181034	Nut, Hex 5M
11	181035	Washer
12	181036	Guide, Push Rod
13	181037	Retainer, Valve Spring
14	181038	Spring, Valve
15	181039	Head, Cylinder
16	181040	Valve
17	180852	Spark Plug
*	181041	Cylinder Head Assembly (Items 13-16)
*	181042	Short Block Assembly (all items from pages 2 & 3)

* not shown

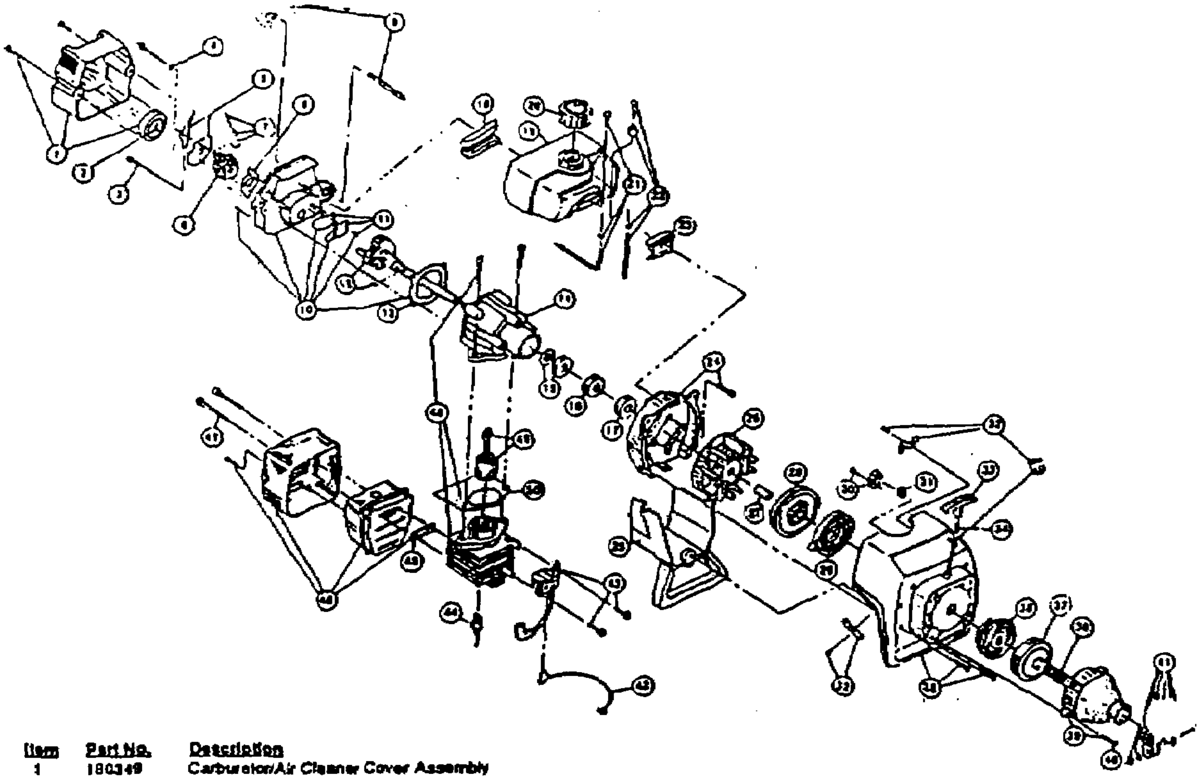


Item	Part No.	Description
1	181000	O-Ring, Push Rod Tube
2	181001	Gasket, Cylinder Head
3	181002	Cylinder
4	181003	Screw, M6 X 18.7mm
5	181004	Gasket, Cylinder
6	181005	Piston Ring Set
7	181006	Pin, Wrist
8	181007	Piston
9	181008	Button, Wrist Pin
10	181009	Rod, Connecting
11	181010	Cylinder Stud (83.5mm)
12	181011	Cylinder Stud (115.5mm)
13	181012	Screw, Cam Bracket
14	181013	Bracket, Cam

Item	Part No.	Description
15	181014	Follower, Cam
16	181015	Cam Gear
17	181016	Seal
18	181017	Crankcase W/Power Shaft (includes items 11, 12 & 17)
19	181018	Gasket, Oil Pan
20	181019	Pan, Oil
21	181020	Screw, M6 X 16.8mm (6 required)
22	181021	O-Ring
23	181022	Plug, Oil Fill (includes item 22)
*	181023	Piston and Rod Assembly (items 6-10)
*	181024	Engine Gasket Kit

* not shown

Figure 14: Exploded view of the Ryobi four-stroke engine.



Item	Part No.	Description
1	180349	Carburetor/Air Cleaner Cover Assembly (Includes item 2)
2	180350	Air Cleaner Filter
3	180351	Carburetor Mounting Screw Assembly
4	180352	Wavey Washer
5	180353	Choke Lever and Plate
6	180527	Carburetor Assembly
7	682048	Throttle Adjustment Assembly (Walbro)
7	180092	Throttle Adjustment Assembly (Zama)
8	610675	Carburetor Gasket (10 pack)
9	683974	Primer and Hose Assembly
10	180354	Carburetor Mount Assembly (Includes items 11 and 13)
11	147573	Reed Assembly
12	180022	Power Shaft Assembly
13	612115	Carburetor Mount Gasket (10 pack)
14	180028	Crankcase Service Assembly (Items 12, 14-17)
15	682041	Inner Bearing Assembly
16	610309	Seal
17	610308	Outer Bearing Assembly
18	612134	Rear Mounting Pad
19	147580	Fuel Tank Assembly (Includes Items 20-22)
20	180000	Fuel Cap Assembly
21	147290	Return Line Assembly
22	682039	Fuel Line Assembly
23	145308	Front Mounting Pad
24	153520	Shroud Assembly
25	683076	Shroud Extension and Stand
26	180829	Flywheel Assembly
27	145918	Spacer
28	180535	Recoil Pulley Assembly
29	613102	Recoil Spring
30	180930	Pulley Retainer Assembly
31	611061	Rope Guide
32	180035	Switch Assembly
33	610300	Pull Handle

Item	Part No.	Description
34	613109	Rope
35	180101	Starter Housing Assembly
36	153591	Clutch Rotor Assembly
37	153592	Clutch Drum Assembly
38	612468	Spring
39	683801	Clutch Cover Assembly
40	145888	Clutch Cover Screw Assembly
41	153597	Upper Clamp Assembly
42	180038	Wire Lead
43	683390	Module Assembly
44	610311	Spark Plug
45	610672	Exhaust Gasket (10 pack)
46	180119	Muffler Assembly
47	147575	Muffler Mounting Bolt Assembly
48	180083	Cylinder Assembly
49	147012	Piston and Rod Assembly
50	610674	Cylinder Gasket (10 pack)
•	180034	Engine Hardware Kit
•	*180011*	*Engine Gasket Kit*
•	153308	O.E.M. Carburetor Repair Kit (Walbro)
•	180090	O.E.M. Carburetor Repair Kit (Zama)
•	153309	Gasket-Diaphragm Repair Kit (Walbro)
•	180091	Gasket-Diaphragm Repair Kit (Zama)
•	180530	Piston Ring
•	180027	Short Block Assembly (Items 12, 14-17, 48-50)
•	610878	Flywheel Key (10 pack)
•	147544	Starter Housing Screw Set

• not shown

Figure 15: Exploded view of a Ryobi two-stroke engine.

Additional Parts - After disassembling the engines, we counted and recorded the parts found in each one. Using this information, which was confirmed against the parts lists in Appendix B, we compiled a list of major parts used in the four-stroke engine that were not found in the two-stroke engine. This list is shown in Table 30. The only major part found in the two-stroke but not in the four-stroke engine was the reed valve assembly in the intake system. We did not include this in our analysis to off-set other minor parts (e.g. washers, screws etc) that were found in the four-stroke engine but not in the two-stroke. For each of the parts in Table 30, we estimated whether it would be more cost-effective to make or purchase. The small parts, such as pivot screws and nuts, were assumed to be purchased, while the bigger and more specialized parts such as the rocker cover, rocker arms, push rod, push rod guide, cam gear and so on would most likely be made in-house. We weighed the manufacturer-produced parts and determined the manufacturing processes required. This information is also presented in Table 30.

Table 30: Information on the additional parts for the Ryobi four-stroke engine as compared to the two-stroke engine.

Item	Unit	Manufacturing Process	Part Material	Weight (lb)
Rocker Box Cover	1	stamping	low-carbon steel	5/64
Rocker Arm	2	stamping	low-carbon steel	1/64
Push Rod	2	precision grinding	low-carbon steel	1/64
Push Rod Guide	2	stamping	low-carbon steel	1/128
Rocker Box	1	die casting	Al alloy	7/64
Oil Pan	1	die casting	Al alloy	1/4
Cam Bracket	1	powder metal	low-carbon steel	3/64
Cam Follower	2	powder metal	low-carbon steel	1/64
Cam Gear	1	powder metal	low-carbon steel	1/8
Crank Gear	1	powder metal	low-carbon steel	1/64
Valve Cover Gasket	1	Purchase from suppliers		
Lock Screw	2			
Pivot Nut	2			
Spring Retainer	2			
Valve	2			
Spring	2			

Other Differences in Parts - Besides the additional parts, there are also differences in manufacturing processes and requirements for similar components when comparing two-stroke and four-stroke engines. Significant differences in terms of manufacturing processes and material requirements were observed in the cylinder head and cylinder block. The cylinder head and cylinder for small two-stroke engines are generally made as one unit, while four-stroke engines have a separate cylinder head. The weight of the four-stroke cylinder/head assembly was found to be about 5/16 lb more than that for the two-stroke engine. This information was used later to estimate the added material cost for these components.

7.2 Cost Analysis

The cost analysis includes an estimate of the variable and fixed costs. We developed incremental cost estimates for a high-volume engine family in a large market share manufacturer and for a high-volume engine family in a small market share manufacturer. The number of engines in a high-volume engine family for large manufacturers (termed Case 1) was determined to be 400,000 units. This number is based on sales information from the PSR database for four of the largest handheld engine manufacturers. The number of engines in a high-volume engine family for small market share manufacturers (termed Case 2) was determined to be 90,000 units. This number is also based on sales information from the PSR database for two typical small handheld engine manufacturers. Further basis for both these numbers is provided in Appendix D.

Variable Manufacturing Costs (Materials, Components, and Labor)

Table 32 shows our estimate of the production costs for the parts that would produced in-house. The data and assumptions on raw material costs and labor costs in this analysis are similar to those that we used in the cost analysis for non-handheld equipment given in Part I. Table 31 shows our estimate of the total change in variable manufacturing costs per engine due to the change from two-stroke to four-stroke. In addition to the costs of manufacturing the parts in-house, the total change in variable costs also includes the purchase cost of those additional parts obtained from outside suppliers. Our estimates of the prices for each of these are shown in Table 31. Purchase cost estimates were discussed with a knowledgeable industry source, who confirmed their accuracy (Conley, 1996).

Table 31: Estimation of manufacturing costs for four-stroke engine parts made in-house.

Part	Valve Cover	Rocker Arm	Push Rod	Push Rod Guide	Rocker Arm Box	Oil Pan	Cam Bracket	Cam Follower	Cam Gear	Crank Gear	Cylinder Head & Cylinder
Process	Stamping	Stamping	precision grinding	Stamping	die-casting	die-casting	Powder Metal	Powder Metal	Powder Metal	Powder Metal	Die Casting
Material	Low Carbon Steel	Low Carbon Steel	Low Carbon Steel	Low Carbon Steel	Al Alloy	Al Alloy	Low Carbon Steel	Low Carbon Steel	Low Carbon Steel	Low Carbon Steel	Al Alloy
Weight (lb)	0.313	0.016	0.016	0.008	0.438	0.250	0.047	0.063	0.125	0.063	0.320
Wgt+10%Scrap	0.344	0.017	0.017	0.009	0.481	0.275	0.052	0.069	0.138	0.069	0.352
Material cost $/lb[2]	0.40	0.40	0.40	0.40	1.00	1.00	0.40	0.40	0.40	0.40	1.00
Material Cost ($/part)	0.138	0.007	0.007	0.003	0.481	0.275	0.021	0.028	0.055	0.028	0.352
Labor minutes	0.5	0.5	1.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	3
Labor cost $/hr	15	15	25	15	15	15	15	15	15	15	25
DL Cost $/part	0.13	0.13	0.63	0.13	0.13	0.13	0.13	0.13	0.13	0.13	1.25
Overhead @40%	0.05	0.05	0.25	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.50
Total cost/part	0.18	0.18	0.88	0.18	0.18	0.18	0.18	0.18	0.18	0.18	1.75
Total mfg. cost/part	0.31	0.18	0.88	0.18	0.66	0.45	0.20	0.20	0.23	0.20	2.10

[1] Incremental manufacturing cost compared to two-stroke engine components

[2] Given the relatively small contribution of material cost to the incremental cost, it was not expected that any volume savings would appreciably change the incremental costs.

In addition to the increased costs of parts, we estimate that the more complex cylinder head and the new valve train would require three extra minutes of assembly labor, costing $1.05 with overhead. The total change in variable manufacturing costs, therefore, comes to $9.93.

Table 32: Estimation of incremental variable manufacturing cost for four-stroke engine compared to two-stroke engine.

	Cost/Piece	Pieces/Engine	Total
Rocker Box Cover	0.31	1	0.31
Rocker Arm	0.18	2	0.36
Push Rod	0.88	2	1.76
Push Rod Guide	0.18	2	0.36
Rocker Box	0.66	1	0.66
Oil Pan	0.45	1	0.45
Cam Bracket	0.20	1	0.20
Cam Follower	0.20	2	0.41
Cam Gear	0.23	1	0.23
Crank Gear	0.20	1	0.20
Valve Cover Gasket	0.25	1	0.25
Lock Screw	0.05	2	0.10
Pivot Nut	0.1	2	0.20
Spring Retainer	0.05	2	0.10
Valve	0.50	2	1.00
Spring	0.25	2	0.50
Cylinder Head & Cylinder	2.10	1	2.10
Total Parts Cost			8.88
Added Assembly Labor			
Labor minutes			3
Labor Cost $/hr			15
Direct Labor $			0.75
Overhead @40%			0.3
Total Labor + OH			1.05
Total Added Variable Manufacturing Cost			**9.93**

Since the variable costs are expressed on a per-engine basis, there would be little difference in these costs between the 400,000 and the 90,000 unit cases. Because of learning-curve effects and economies of mass production, we would anticipate that the actual variable costs for the 400,000 unit case would be a little smaller, but these differences are difficult to quantify without much more detailed information.

Fixed Costs

Our estimates of fixed costs are presented in Table 33. Although Ryobi is selling four-stroke engines for the handheld equipment, and Honda has announced that it will have one four-stroke model for handheld equipment in 1997, other engine manufacturers will still require quite extensive research, design and development work before they can market their own four-stroke engines for handheld equipment. This is especially true for those handheld engine manufacturers that have been dealing with only two-stroke engines for decades.

The development work required to convert a two-stroke engine to four-stroke operation was estimated to require about three engineer-years of effort, costing about $300,000 with overheads. The estimated cost was based on information from Ryobi's experience, and the assumption that the next manufacturers will benefit (i.e., less engineering design) from Ryobi's effort. The costs for the emission testing would also be fairly high, since it would require more testing to develop a new engine than to improve an existing one. We estimated that the development would require 500 emission tests at $300 per test, for a total of $150,000. Additional engineering-related costs of $100,000 were estimated to cover prototype development, test engines, travel, test materials and similar costs. The total engineering cost was estimated at $550,000. These costs would not be greatly different between the 400,000 and the 90,000 unit cases.

Changing an engine line would also require extensive expenditure for technical support, training and publications. We assumed it would cost about $500,000 for the high-volume model and $200,000 for the low-volume model. This is consistent with information from Honda (1996) on the costs of technical support for a major engine modification.

Tooling costs would include the costs of new master dies for die-casting the cylinder head, cylinder block, oil pan, connecting rod, piston, and crankshaft; and new stamping dies for the rocker cover, rocker arm, and push rod guide. New molds would also be needed for powder metal forming of the cam bracket, cam follower, cam gear and crank gear. Cost estimates for these dies were based on our conversations with industry sources, as referenced earlier in Part I. Total tooling costs would amount to about $300,000 for the 400,000 unit case and $250,000 for the 90,000 unit case. This includes setup costs estimated at $100,000 and $50,000, respectively. The setup cost includes the changes in the assembly process, material handling, jigs, fixtures, machine settings, etc. needed to integrate the new machines into the assembly flow (similar to SV to OHV conversion).

Table 33: Estimated fixed costs for converting two-stroke to four-stroke engines for handheld equipment.

	Case 1	Case 2
Engineering Costs		
Engineering labor + OH (3 years @ $100,000)	300,000	300,000
Number of Tests	500	500
Test Cost ($)	300	300
Testing costs	150,000	150,000
Other engineering	100,000	100,000
Total Engineering	550,000	550,000
Technical support		
Training/Tech. Pubs	500,000	200,000
Tooling Costs		
New Master Dies		
Cylinder head	30,000	30,000
Cylinder block	30,000	30,000
Connecting rod	10,000	10,000
Piston	10,000	10,000
Crankshaft	15,000	15,000
Rocker Cover	10,000	10,000
Rocker Arm	10,000	10,000
Push Rod Guide	10,000	10,000
Oil Pan	15,000	15,000
Cam Bracket	15,000	15,000
Cam Follower	15,000	15,000
Cam Gear	15,000	15,000
Crank Gear	15,000	15,000
Setup changes	100,000	50,000
Total tooling	300,000	250,000
Total Engine-Specific	1,350,000	1,000,000
Amortized over 5 yrs	347,075	257,092
New Machine Tools	2,225,000	730,000
Amortized over 10 yrs	346,700	111,258
Total Fixed Cost/Yr	693,775	368,350
Annual Production	400,000	90,000
Fixed cost/engine	1.73	4.09

Total engine specific costs were estimated at $1,350,000 for the high-volume model, and $1,000,000 for the low-volume model. These costs were amortized over five years at a cost of capital of 9%. The total amortized fixed costs amount to about $347,000 per year for the 400,000 unit case and $257,000 per year for the 25,000 unit case. The costs of new machine tools (stamping presses, powder-metal forming machines, and die-casting machines) were estimated at $2.225 million for the 400,000 unit case, and $730,000 for the 90,000 unit case. Amortizing these costs over a ten-year period at a 9% capital rate, the new machine costs per year were $347,000 for the high-volume case and $111,000 for the low-volume case. Summing all the fixed costs and dividing by the number of units produced results in fixed costs of $1.73 per engine for the 400,000 unit case, and $4.09 per engine for the 90,000 unit case.

Table 34 is a summary of total hardware/assembly costs and fixed costs for converting two-stroke to four-stroke engines for handheld equipment.

Table 34: Summary of the total added manufacturing and fixed costs for converting 2-stroke to 4-stroke handheld engines.

	Case 1	Case 2
Total Added Manufacturing Cost	9.93	9.93
Fixed Costs	1.73	4.09

Actions by Small Manufacturers to Reduce Costs to Convert from Two- to Four-Stroke Engines

There may be only a few manufacturers in the handheld engine market that can be characterized as small manufacturers. Most small engine manufactures with small market share (Tecumseh, Kioritz) are medium to large companies with the ability to afford extensive capital investment. We expect that any actual small engine manufacturer is less likely to make this two- to four-stroke conversion than a large manufacturer because of the costs for designing and manufacturing a new technology engine and because of the additional costs of redesigning the equipment to handle the different size and weight of the four-stroke engine. Even if we assume that the small manufacturer will make the conversion from two- to four-stroke, the manufacturer may not go about it the same way as it had in the past in producing the two-stroke family line. We anticipate that the small engine manufacturer may make certain decisions to reduce the costs of this conversion. For example, the small engine manufacturer may not be able to afford the capital investment necessary to purchase new machine tools to make their own cylinder head and block (which is necessary for a new 4-stroke design). Also, the small manufacturer may not have the engineering labor to pursue the extensive design effort to develop this new and complex engine. Consequently, the small manufacturer may purchase the four-stroke engines from a larger handheld engine manufacturer. On balance between savings both capital and engineering labor and the need to purchase the engines, the small manufacturers may realize a modest savings over manufacturing the engines themselves.

Also, the small manufacturer may not have to incur costs for developing new training/technical/catalogue publications if they purchase and adapt the publications from the manufacture that sold them the engines. This could perhaps result in additional savings over the estimated costs for a small manufacturer to develop training/technical/catalogue publications. We assume that some of the above cost savings decisions would be implemented by a small manufacturer.

8. COST ANALYSIS FOR IMPROVING TWO-STROKE ENGINES

This chapter presents our incremental cost estimates for improvements in the scavenging of two-stroke engines by optimizing the designs of the piston, ports, and combustion chamber; and for the application of stratified scavenging using a throttle valve. Again, we assumed that a large handheld manufacturer (case 1) had a high-volume engine line of 400,000 units and a small handheld manufacturer (case 2) had a high-volume line of 90,000 units (see Appendix D for basis).

8.1 Two-Stroke Engines with Improved Scavenging

Substantial HC emission reductions can be realized by optimizing the piston and port designs to reduce scavenging losses. The use of better piston and port designs, such as the GPB's deflector piston/port designs (Blair, 1996); and/or the use of an optimized combustion chamber, such as the GUT "Jockey-cap" combustion chamber (Laimbock and Landerl, 1990) can also allow the use of a leaner mixture without jeopardizing the engine performance. A leaner mixture and better combustion characteristics result in lower HC and CO emissions. Thus, a two-stroke engine with optimized piston, port, and combustion chamber designs, along with a better quality carburetor, could be a potential option to meet the Phase 2 emission standards or even more stringent standards. It would also provide a less harsh environment for an oxidation catalyst to perform its job by reducing engine out HC and CO emissions. Therefore, we have developed a cost analysis based on these improvements.

Optimization of piston, port, and combustion chamber designs would not require additional parts or machining processes, but only refinements in the design of existing parts. The effect on variable manufacturing costs, therefore, will be very small, and could be either positive or negative. For purposes of this analysis, we assume that the design changes would not affect variable costs, but only the fixed costs of production.

Fixed Costs

Our estimates of the fixed costs of optimizing piston, port, and combustion chamber designs are shown in Table 35. The design of an improved two-stroke handheld engine is somewhat more complex than the design for an improved side-valve non-handheld engine because of the tighter tolerances needed on a smaller engine. Also, the designer has less flexibility in what can be done with a two-stroke design, and may, therefore, need additional effort. We estimate that the development of an optimal design would require about two engineer-years, at a cost of about $200,000 for labor and overheads. Emission testing costs were estimated at $90,000. Other engineering-related costs such as prototype engines, travel, test materials and so forth are estimated at $50,000. The total engineering cost is estimated at $340,000. These costs would be nearly the same for either the 400,000 or the 90,000 unit cases.

Updating the parts lists and similar information to incorporate the redesigned parts is estimated to cost $20,000. New master dies would be required for the cylinder/cylinder head, piston, and carburetor. Costs of these dies were estimated based on our conversations with industry sources and die makers (Spec Cast, 1996). Set-up costs of $50,000 for the high-volume case and $25,000 for the low-volume case were also estimated. Total engine specific costs would be $525,000 for the high-volume model, and $500,000 for the low-volume model. These costs were amortized over five years at a cost of capital of 9%. The total amortized fixed costs amount to about $135,000 per year for the 400,000 unit case and $129,000 per year for the 90,000 unit case. Dividing these estimates by the number of units produced results in fixed costs of $0.34 and $1.43, respectively.

Table 35: Estimated fixed costs for two-stroke engines with improved scavenging.

	Case 1	Case 2
Engineering Costs		
Engineering labor + OH (2 year @ $100,000)	200,000	200,000
Number of Tests	300	300
Test Cost ($)	300	300
Testing costs	90,000	90,000
Other engineering	50,000	50,000
Total Engineering	340,000	340,000
Technical support		
Training/Tech. Pubs	20,000	20,000
Tooling Costs		
New Master Dies		
Cylinder/Cylinder Head	40,000	40,000
Piston	15,000	15,000
Carburetor	60,000	60,000
Total Tooling	115,000	115,000
Machine Tool Setup	50,000	25,000
Total Engine-Specific	525,000	500,000
Amortized over 5 yrs	134,974	128,546
New Machine Tool	0	0
Amortized over 10 yrs	0	0
Total Fixed Cost/Yr	134,974	128,546
Annual Production	400,000	90,000
Fixed cost/engine	**0.34**	**1.43**

8.2 Two-Stroke Engines with Stratified Scavenging

A well designed stratified scavenging system in a two-stroke engine with optimized piston, port, and combustion chamber designs can be expected to reduce full-power HC emissions by 30% to 50%. In this section, we estimate the incremental costs for a stratified scavenging system.

Variable Manufacturing Costs

The stratified scavenging approach would involve changes in the air system to prefill the transfer ports with air instead of air-fuel mixture. This would require adding new hardware to the engine, and would thus increase variable costs. Our estimate of these variable costs is shown in

Table 36. As shown in the table, we estimated that the throttle valve would cost about $0.50 from an external supplier, and we assumed another $0.50 for extra fittings. We also estimated that it would require one minute of added labor time (costing $0.58 with overhead) for handling and assembling the added parts. These costs would be roughly the same for both high and low volume cases.

Table 36: Manufacturing costs for additional parts for two-stroke engine with stratified scavenging.

	Cost/ Piece	Pieces /Engine	Total
Throttle Valve	0.50	1	0.50
Other Fittings			0.50
Total Parts Cost			1.00
Added Assembly Labor			
Labor minutes			1
Labor Cost $/hr			25
Direct Labor $			0.42
Overhead @40%			0.17
Total Labor + OH			0.58
Total Added Mfg. Cost			**1.58**

Fixed Costs

Our estimates of fixed costs are tabulated in Table 37. The fixed costs for the development of two-stroke engines with optimized piston, port and combustion chamber designs, improved carburetor, and a stratified scavenging system would be about the same as those for the optimized two-stroke engines without stratified scavenging. For this case, however, we estimated that 400 emission tests would be required instead of 300, since more tests would be needed to develop the stratified scavenging system. The costs for technical support, training, and publications were estimated to be higher as well - $100,000 for the high-volume model and $50,000 for the low-volume model. This is intermediate between the costs of a technical bulletin and those of a complete revision to engine documentation.

Total engine specific costs were estimated at $635,000 for the high-volume model, and $560,000 for the low-volume model. These costs were amortized over five years at a cost of capital of 9%. The total amortized fixed costs amount to about $163,000 per year for the 400,000 unit case, and $144,000 per year for the 90,000 unit case. Dividing these estimates by the number of units produced results in fixed costs of $0.41 per engine for the high volume case, and $1.60 per engine for the low volume case.

Table 38 is a summary of hardware/assembly costs and fixed costs for two-stroke engines with stratified scavenging.

Table 37: Estimated fixed costs for two-stroke engines with stratified scavenging.

	Case 1	Case 2
Engineering Costs		
Engineering labor + OH (2 year @ $100,000)	200,000	200,000
Number of Tests	400	400
Test Cost ($)	300	300
Testing costs	120,000	120,000
Other engineering	50,000	50,000
Total Engineering	370,000	370,000
Technical support		
Training/Tech. Pubs	100,000	50,000
Tooling Costs		
New Master Dies		
Cylinder/Cylinder Head	40,000	40,000
Piston	15,000	15,000
Carburetor	60,000	60,000
Total Tooling	115,000	115,000
Machine Tool Setup	50,000	25,000
Total Engine-Specific	635,000	560,000
Amortized over 5 yrs	163,254	143,972
New Machine Tool	0	0
Amortized over 10 yrs	0	0
Total Fixed Cost/Yr	163,254	143,972
Annual Production	400,000	90,000
Fixed cost/engine	**0.41**	**1.60**

Table 38: Summary of the variable and fixed costs for 2-stroke with stratified scavenging.

	Case 2	Case 3
Total Added Manufacturing Cost	1.58	1.58
Fixed Costs	0.41	1.60

9. COST ANALYSIS FOR TWO-STROKE ENGINES WITH CATALYST

A catalytic converter can be added to a two-stroke engine to reduce emissions. However, the use of catalyst technology alone may not be sufficient to meet both emission limits and the U.S. Forest Service limits on exhaust temperature. If a catalytic converter with a high efficiency were used, the exothermic energy released by the oxidation of HC and CO would be very high. The resulting catalyst temperature would exceed the thermal limits of the catalytic converter (roughly 1,000 °C), as well as exceeding the USFS limits on exhaust and skin temperatures. If a catalytic converter with a low efficiency were used, the emission reductions might not be sufficient to meet the standards in the Statement of Principles for EPA Phase 2 regulations of handheld engines. Thus, the key requirement in each of these approaches is to reduce the engine-out HC and CO emission levels to the point that a catalytic converter can survive in the exhaust without overheating, and if possible to achieve an overall lean or stoichiometric air-fuel ratio in the exhaust to maximize catalytic converter efficiency. It is then possible to rely on the catalytic converter to bring the remaining HC and CO to levels well below the applicable standards.

A wide variety of emission control measures and design features could be used to achieve the further reduction in engine-out HC and CO emissions needed to allow the catalytic converter to survive in the exhaust. Some of these measures have already been discussed in previous chapters. Since it is not always clear what technology a manufacturer would use in conjunction with the catalyst technology, we assessed the costs only for the application of the catalyst technology. These costs can then be combined with the cost estimates for improved two-stroke engines with or without a stratified scavenging system, or with those for converting to a four-stroke engine. As in the previous chapters, a manufacturer with a large market share (case 1) was assumed to produce 400,000 engine per year, and a manufacturer with a small market share (case 2) to produce 90,000 engines (see Appendix D for basis).

9.1 Two-Stroke Engines with Catalyst

Variable Manufacturing Costs - The use of catalyst in a two-stroke engine would require some hardware or variable costs, such as the costs for the catalyst and heat shield. These variable costs are tabulated in Table 39. As shown in the table, we estimated that the ceramic catalyst would cost about $4.00 (Allied Signal and United Emission Catalyst, 1996). If a metallic catalyst is used, we estimated that the cost would be doubled (i.e. $8.00). The costs of the heat shield and the heat-resistant muffler are accounted for in the equipment cost analysis given in Chapter 10, and are not duplicated here to avoid double-counting.

We estimated that the catalytic converter production would require one minute of added labor time (costing $0.58 with overhead) for handling and the relatively straightforward assembly of added parts (Ostwald, 1994, Winchell, 1989) performed by skilled labor. These costs would be applicable to both high and low volume models.

Table 39: Manufacturing costs for additional parts for two-stroke engine with catalyst.

	Ceramic	Metallic
Catalyst	4.00	8.00
Added Assembly Labor		
Labor minutes	1	1
Labor Cost $/hr	25	25
Direct Labor $	0.42	0.42
Overhead @40%	0.17	0.17
Total Labor + OH	0.58	0.58
Total Added Mfg. Cost	**4.58**	**8.58**

Fixed Costs - Our estimates of the fixed costs involved in applying a catalytic converter to a two-stroke engine model are shown in Table 40. We estimate that the development effort would require about two engineer-years of work, costing $200,000 with overhead. The relatively large amount of effort required is due to the lack of existing experience with catalytic converters. The number of emission tests would be more than that needed for a minor redesign, but perhaps less than for a major redesign (two to four stroke). We assumed a total of 400 emission tests at a cost of $120,000 for baseline, prototype and other emission testing. Other engineering-related costs were estimated at 50,000. The costs for technical support, training, and publications were estimated at $100,000 for the high-volume model and $50,000 for the low-volume model, reflecting the need for safety and technical training of service personnel, as well as changes in parts lists and similar documents.

Table 40: Estimated fixed costs for two-stroke engines with catalyst.

	Case 1	Case 2
Engineering Costs		
Engineering labor + OH (2 year @ $100,000)	200,000	200,000
Number of Tests	400	400
Test Cost ($)	300	300
Testing costs	120,000	120,000
Other engineering	50,000	50,000
Total Engineering	370,000	370,000
Technical support		
Training/Tech. Pubs	100,000	50,000
Tooling Costs		
Total Engine-Specific	470,000	420,000
Amortized over 5 yrs	120,833	107,979
New Machine Tool	0	0
Amortized over 10 yrs	0	0
Total Fixed Cost/Yr	120,833	107,979
Annual Production	400,000	90,000
Fixed cost/engine	**0.30**	**1.20**

The addition of a catalytic converter to a two-stroke engine would not in itself require any tooling costs. The changes in the design of the muffler, heat shield, and other components of the engine-powered equipment would involve tooling costs, but these are addressed separately in Chapter 10. Thus, the total engine-specific costs would be about $470,000 for the high-volume model, and $420,000 for the low-volume model. These costs were amortized over five years at a cost of capital of 9%, resulting in annual fixed costs of $121,000 and $108,000, respectively. Dividing these estimates by the number of units produced results in fixed costs of $0.30 per engine for the 400,000 unit model, and $1.20 per engine for the 90,000 unit model.

Table 41 is a summary of total hardware/assembly and fixed costs for two-stroke engines with a catalytic converter.

Table 41: Summary of total hardware/assembly costs and fixed costs for two-stroke engines and catalyst.

	Case 1	Case 2
Hardware/Assembly Costs	$4.58[1] $8.58[2]	$4.58[1] $8.58[2]
Fixed	0.30	1.20

[1] ceramic substrate
[2] metallic substrate

9.2 Improved Engine Designs with Catalyst

As discussed previously, a catalytic converter could be combined with any of the other advanced two-stroke options considered in this report to achieve even lower emissions. Table 42 summarizes the total hardware/assembly costs and fixed costs for the combination of the catalytic converter with optimized scavenging, stratified scavenging system, and the two-stroke to four-stroke conversion .

Table 42: Summary of total hardware/assembly costs and fixed costs for improved two-stroke engines with catalyst, two-stroke engines with stratified scavenging and catalyst, and 2-stroke to 4-stroke conversion with catlyst.

	Case 1	Case 2
Improved 2-Stroke Engine with Catalyst		
Hardware/Assembly Costs	$4.58[1] $8.58[2]	$4.58[1] $8.58[2]
Fixed	0.64	2.63
2-Stroke Engines with Stratified Scavenging and Catalyst		
Hardware/Assembly Costs	$6.16[1] $10.16[2]	$6.16[1] $10.16[2]
Fixed	0.71	2.80
2-Stroke to 4-Stroke Engine Conversion with Catalyst		
Hardware/Assembly Costs	$14.51[1] $18.51[2]	$14.51[1] $18.51[2]
Fixed	2.03	5.29

[1] with ceramic substrate catalytic converter
[2] with metallic substrate catalytic converter

PART III

EQUIPMENT COSTS, USER COSTS AND CONSTRAINTS

10. COST ESTIMATE TO ADAPT EQUIPMENT TO MODIFIED ENGINE TECHNOLOGIES

The types of engine modification technologies evaluated in Parts I and II may have impacts on the design of equipment. Some equipment may be sensitive to engine orientation, weight, size, location of exhaust/air filter/oil disposal, higher engine exhaust heat, and other factors. In this chapter, the types of changes in equipment design/production and the associated costs are examined.

For the six technologies examined in this study, Table 43 presents some features (e.g., size, weight) of the modified engines that might result in downline equipment changes.

Table 43: Features of the Modified Engines that Might Result in Equipment Changes.

Engine Modification	Features of the Modified Engines that Might Result in Equipment Changes
Convert SV to OHV (NHH)	OHV taller, weighs more, but in terms of width, two single cylinder SV in opposed configuration is roughly equal to V-Twin OHV
Improved SV (NHH)	None expected
Improved OHV (NHH)	None expected
Convert Two to Four-Stroke (HH)	Currently four-stroke weighs perhaps 2-3 pounds more, but still under 8 pounds total; more bulky
Improved Two-Stroke (HH)	None expected
Added Catalyst to Two-Stroke (HH)	More bulky and new heat source from catalyst

Based on this table, it is not expected that any costs will be incurred by the equipment manufacturer by installing improved two-stroke, improved SV, or improved OHV. Thus, the remaining focus is on the three remaining engine modification technologies.

Any changes in equipment as a result of an engine change or modification depend on the equipment application. Consequently, the major applications in each engine class were identified using the Power Systems Research ENGINDATA database and to a lesser extent, on the CARB certification database. Table 44 lists the applications that made up a large segment of the engines sold or that had a large number of engine families/models. Additionally, the listing includes minor applications that may require different equipment design changes than those of the major application equipment. Based on this listing, we focused on manufacturers of lawn and garden equipment, generators, and pumps. Some other equipment (e.g., golf cart) which are similar to certain lawn and garden equipment may require similar changes. The following cost analyses first addresses non-handheld equipment and then handheld equipment.

Table 44: Major applications of small engines, by engine class.

	(of total)		(of total)		(of total)		(of		(of
mower/comm turf	81.5%	tractor	53.0%	trimmer/cut'r	NA	trimmer/cut'r	80.0%	chain saw	53.2%
tiller/snowblower	8.1%	mower/comm turf	12.2%			chain saw	11.5%	mower	29.0%
generator	2.7%	generator	10.8%			blower/vacuum	4.8%	snowblo-	17.7%
compressor/wash	1.1%	snowblower	5.7%			pump	1.2%		
pump	1.1%	golf cart	3.5%						
leaf blower	0.5%	tiller	2.5%						
shredder	0.5%	outboard engine	2.1%						
sprayer	0.1%	compressor/washer	1.8%						
wood splitter	0.1%	pump	1.6%						
mixer	0.1%	welder	1.5%						
plate compactor	0.1%	shredder/chipper	0.8%						
other	4.0%		4.5%				2.5%		0.0%
Total	100.0%		100.0%		NA		100.0%		100.0%

Source: PSR database (sales data for 1993)
Note: sales for classes I & II do not include exported engines, or engines sold directly by engine distributors

10.1 Non-Handheld Equipment

We contacted over ten equipment manufacturers, representing a variety on non-handheld applications, however, only a few responded or could provide the desired equipment modification or cost information.

Walk Behind Lawnmowers

Currently, most walk behind lawnmowers use SV technology. Conversion from side-valve to OHV is viewed as incurring little if no additional costs because there is extensive room over the blade area to mount the slightly larger OHV and also the engines also are not enclosed in a covering. The mounting pads would not need to be changed. SV and OHV are sometimes interchanged with very minor changes within model lines. (MTD conversation, September 1996).

Rear Engine Rider

In rear engine riders, the engine is usually exposed (i.e., not covered by hood). Because the OHV is taller than the SV, the OHV engine will need to be reoriented 90 degrees from the traditional side-valve so that the cylinder is parallel to the center line of the equipment. This affects several equipment features including the mounting holes, the controls, the exhaust, and the oil drains (John Deere conversation, September 1996). The cost impact of these and other factors are summarized in Table 45.

Table 45: Cost of Equipment Changes for Rear Engine Rider as a Result of SV to OHV Conversion.

Change	Action	Cost
Change in Mounting Holes	Change blanking die to add 4 holes	$40,000-$100,000 for die and tooling per equipment line
Control Wires Longer Because of Reorientation	Need additional material	Minor
Modified Exhaust/Air Filter Positioning	New tooling by exhaust supplier and new materials	$10,000 to $100,000 depending on extent of tooling; material costs directly passed to consumer
Study of Vibration	R&D	probably one time cost for all engine families
Relocate Oil Drains	Punch blanking hole in die or install drain tube on engine	$10,000 per equipment line for die or $2 to OEM per piece of equipment

Source: Conversations with John Deere and American Yard Products

Lawn Tractor

Lawn tractors (approximately 9-16 hp) usually have a hood covering over the engine. Because of the greater length of the OHV, the hood will need to be lengthened. This can be an expensive change. Usually, it requires a new injection molding die to create a redesigned plastic hood. Costs for a hood modification range from $300,000 to 1.5 million dollars per equipment line (John Deere conversation September 1996 and American Yard Products conversation September 1996). Typical equipment dies last 3-10 years and produce upwards of 250,000 units. Other costs are similar to the rear engine rider though additional baffling will be needed. The costs are delineated in Table 46. Although not usually included in lawn tractors, a fuel shutoff solenoid valve may be required to prevent any bleeding of gas into the muffler and any resulting explosion or flaming in the muffler after the equipment is turned off. This may occur more in OHV engines because OHV engines tend to run leaner and hotter. However, the cost for the solenoid is not included below in the cost for lawn tractors.

Table 46: Cost of Equipment Changes for Lawn Tractor as a Result of SV to OHV Conversion.

Change	Action	Cost
Hood Lengthen	New master die and tooling	$300,000 - $1,500,000 per equipment line
Change in Mounting Holes and Brackets	Change blanking die to add 4 holes	$40,000-$100,000 for die and tooling per equipment line
Control Wires Longer Because of Reorientation	Need additional material	Minor
Modified Exhaust/Air Filter Positioning	New tooling by exhaust supplier and new materials	$10,000 to $100,000 depending on extent of tooling; material costs directly passed to consumer
Study of Vibration	R&D	probably one time cost for all engine families
Relocate Oil Drains	Punch blanking hole in die or install drain tube on engine	$10,000 per equipment line for die or $2 to OEM per piece of equipment
Additional Baffling	Tooling	$20,000-$30,000

Source: Conversations with John Deere and American Yard Products

Lawn and Garden Tractors

For lawn and garden tractors, (typically 18-25 hp), the OHV will not have to be reoriented because the cylinder head is always facing forward. Therefore, mounting holes would not be an issue. Additionally, there is typically room under the hood to handle a V-twin OHV engine. However, additional baffling will be needed. Also, the fuel shutoff solenoid is added to prevent explosion in muffler and flame from muffler. The costs are delineated in Table 47.

Snowblower/Tiller

The costs for adapting a snowblower/tiller to use an OHV in place of a SV was estimated to be approximately one-third the cost of adapting the lawn tractor (American Yard Products conversation, September 1996).

Table 47: Cost of Equipment Changes for Lawn and Garden Tractor as a Result of SV to OHV Conversion.

Change	Action	Cost
Modified Exhaust Positioning	New tooling by exhaust supplier and new materials	$10,000 to $100,000 depending on extent of tooling; material costs directly passed to consumer
Study of Vibration	R&D	probably one time cost for all engine families
Relocate Oil Drains	Punch blanking hole in die or install drain tube on engine	$10,000 per equipment line for die or $2 to OEM per piece of equipment
Redesign Baffle	Tooling	$20,000-$30,000
Fuel Shutoff Solenoid	Add/integrate equipment	$8-15 to OEM

Source: Conversations with John Deere and American Yard Product

Generator Sets

Generator sets are usually encased in a frame that holds the engine and other parts of the generator set. For some generator set lines, the taller OHV may require that the frame or cage around the generator set be redesigned, developed, tooled, and fabricated. Often, the fuel tank will also need to be redesigned and the muffler relocated. Table 48 lists the costs of these changes per equipment line. At least six months would be needed to implement this change (John Deere conversation, September 1996).

Table 48: Cost of Equipment Changes for Generator Sets as a Result of SV to OHV Conversion.

Change	Action	Cost
Expand Frame, Redesign Fuel Tank, and Relocate Muffler	Redesign, develop, tool, fabricate	$100,000 per equipment line

Source: Conversation with John Deere

Pumps

Like the generator sets, some pumps that are encased in a frame or cage may need to be redesigned, developed, tooled, and fabricated. Often, the fuel tank will also need to be redesigned and the muffler relocated. Table 49 lists the costs of these changes per equipment line. At least six months would be needed to implement this change (John Deere conversation, September 1996).

Table 49: Cost of Equipment Changes for Pumps as a Result of SV to OHV Conversion.

Change	Action	Cost
Expand Frame, Redesign Fuel Tank, and Relocate Muffler	Redesign, develop, tool, fabricate	$50,000 per equipment line

Source: Conversations with John Deere

10.2. Modifications to Handheld Equipment due to Engine Changes

With few exceptions, manufacturers of handheld equipment produce their own engines. Thus, engine modifications and equipment modifications are likely to be closely coordinated. Engine modifications that are likely to require a change in equipment design include the conversion from two-stroke to four-stroke engines, and the addition of a catalytic converter to two-stroke engines. In our judgement, internal improvements to the two-stroke engine are not likely to require changes in the equipment design.

Two-stroke to four-stroke conversion - Four-stroke engines are currently larger and heavier than two-stroke engines. On nearly all string trimmers and hand-held blowers, the engine is enclosed in a set of injection-molded plastic components, which together make up the external body of the equipment. Chainsaws would also be included in this group, however, the chainsaw will not be specifically mentioned because of questions about the feasibility of using a four-stroke engine on applications that require multipositional capability. The significant change in engine size and shape due to changing to four-stroke operation will require changes in the design of the trimmer and blower. This will require new injection molds, at a minimum, and may require additional material as well. This additional weight is a concern given the equipment is weight sensitive and the four-stroke already weighs more than the two-stroke. On the other hand, backpack blowers, portable pumps, and similar equipment generally do not enclose the engine in plastic. For most of these units, the only equipment change needed would be a minor change in the design of the stamped metal retaining strap attached to the engine.

We compared the external plastic components used in the Ryobi two-stroke string trimmer with those used in the Ryobi four-stroke trimmer. The results of this comparison are shown in Table 50. Analysis of the changes is complicated by the fact that some changes were obviously made for purposes of styling and/or user comfort, and were not directly attributable to the change from two-stroke to four-stroke design. The design changes also succeeded in eliminating one component (the stamped steel muffler shield) by increasing the size of the engine cover, and reducing the number of injection-molded components in the starter housing and shaft support from three to two. The total weight of injection molded components increased by 9.5 ounces.

In our view, neither the elimination of the two parts nor the increase in weight of the injection-molded parts between the Ryobi four-stroke trimmer and the earlier two-stroke trimmer are attributable to the change from two-stroke to four-stroke operation. Instead, these were attributable to design and styling improvements that are normally incorporated with any new model.

Table 50: Comparison of equipment parts for a 2-stroke and a four-stroke engine.

Part	Weight (oz)		Material	Manufacturing Process
	2-Stroke	4-Stroke		
Air-Cleaner Cover	2	3	Plastic	Injection Molding
Shroud Extension and Stand	2.5	n/a	Plastic	Injection Molding
Starter/Fan Housing Assembly	9.5	8.5	Plastic	Injection Molding
Throttle/Handle Housing (left/top)	1.5	6	Plastic	Injection Molding
Throttle/Handle Housing (right/bottom)	1.5	6	Plastic	Injection Molding
Clutch Cover	2	n/a	Plastic	Injection Molding
Muffler Cover	5	n/a	L.C. Steel	Stamping
Engine Cover	n/a	5	Plastic	Injection Molding
Muffler	8.5	8.5	L.C. Steel	Stamping
Total Parts Number	8	6		
Total Weight: Plastic	19	28.5		
Total Weight: L.C. Steel	13.5	8.5		

The change from two-stroke to four-stroke operation will also require some changes in the design of the muffler, as the location of the exhaust discharge from the engine is different between the two designs. A typical muffler consists of three stamped sheet metal pieces joined together. While it might be possible to accommodate the change in location with a change in only one of these pieces, we anticipate that a change in all three pieces would be required in most cases. This would require changes in the three stamping dies used to make these pieces. In the case of the Ryobi engines, the change from two-stroke to four-stroke also made possible the incorporation of an integral spark arrestor into the muffler, thus adding two more components: a stamped steel plate and a section of metal screen. These were not counted as an incremental cost due to the change, since they represent a product enhancement rather than a change made necessary by the change from two-stroke to four-stroke.

Based on our comparison of the two Ryobi models, no incremental variable costs are assignable to the equipment changes required to accommodate the four-stroke engine. However, the changes in the design of the muffler stamping would require new stamping dies, and the changes in the design of the air cleaner cover, fan housing cover, and engine cover would require new injection molds. These would not be required for pumps and backpack blowers. The engine cover for pumps and backpack blowers is stamped metal strap, which would require a new stamping die. No new machine tools would be required, since only the shape of the components is changed, and not the number or basic manufacturing processes. We estimate that about six months of engineering time would be required to make the needed design changes and confirm the performance of the modified designs (three months for the pumps and backpack blowers). Although the needed changes are straightforward, they would involve a significant amount of detail. Miscellaneous engineering-related costs would include performance and safety testing and similar costs. These are estimated at $20,000 for chainsaws, trimmers, and handheld blowers, and $10,000 for backpack blowers and pumps. The estimated costs for the technical publications and training are consistent with an independent cost estimate for a minor engine/equipment modification (Honda, 1996). Detailed cost estimates are shown in Table 51.

Table 51: Estimated equipment fixed costs for converting 2-stroke engines to 4-stroke engines.

Fixed Costs	Chainsaws, Trimmers etc.		Backpack Blowers and Pumps	
	Case 1	Case 2	Case 1	Case 2
Engineering Costs				
Engineering labor (person year)	0.5	0.5	0.25	0.25
Engineering labor + OH	50,000	50,000	25,000	25,000
Number of Tests	0	0	0	0
Test Cost ($)	250	250	250	250
Testing costs	0	0	0	0
Other engineering	20,000	20,000	10,000	10,000
Total Engineering	70,000	70,000	35,000	35,000
Technical support				
Training/Tech. Pubs	20,000	20,000	10,000	10,000
Tooling Costs				
New Injection Molds				
Air Cleaner Cover	5,000	5,000	0	0
Fan Housing Cover	20,000	20,000	0	0
Engine Cover	10,000	10,000	0	0
New Stamping Dies				
Muffler, Top	5,000	5,000	5,000	5,000
Muffler, Bottom	5,000	5,000	5,000	5,000
Muffler, Baffle	5,000	5,000	5,000	5,000
Engine Retainer Strap			5,000	5,000
Setup changes	20,000	20,000	10,000	10,000
Total tooling	70,000	70,000	30,000	30,000
Total Engine-Specific	160,000	160,000	75,000	75,000
Amortized over 5 yrs	41,135	40,603	19,282	19,032
New Machine Tools	0	0	0	0
Amortized over 10 yrs	0	0	0	0
Total Fixed Cost/Yr	41,135	40,603	19,282	19,032
Annual Production	400,000	90,000	400,000	90,000
Fixed cost/engine	0.10	0.45	0.05	0.21

The costs of sheet metal stamping dies can range from $5,000 for a simple die to substantially higher (Conley, 1996). Since the muffler components are all relatively simple stamping, we estimated a die cost of $5,000 each. Injection molds can also range from $5,000 for a simple one up to much higher costs. The mold for the air cleaner cover would be simple, while that for the fan housing is more complex, and that for the engine cover is of intermediate complexity. These costs were estimated at $5,000, $20,000, and $10,000, respectively. Adjustments to other tooling and new jigs to accommodate the changed size and shape of the parts are estimated to cost an additional $20,000 ($10,000 for the backpack blowers and pumps).

Catalytic converters in two-stroke engines - The addition of a catalytic converter to a two-stroke engine would also require changes in the design of various equipment (including trimmer, chainsaw, blower). The catalytic converter would be incorporated into the muffler, necessitating changes in the design of all three of the muffler stamping. Since the exhaust temperature will also increase greatly, it will be necessary to change the muffler material from the present low-carbon steel to a more expensive alloy steel such as 405 (chromium alloy) or 304 (nickel-chromium alloy) that will retain its strength at higher temperatures. We estimate that this will double the material costs for the muffler to about $0.80 per pound. A local metal supplier (ABC supply, 1996) quoted prices of $0.80 per pound for cold-rolled 1080 low-carbon steel sheet, and $1.50 per pound for 304 alloy sheet, about twice as much. Large buyers are able to obtain much lower prices (Am. Metal Market, 1996). Quotes for 405 alloy sheet were not available, but the cost is expected to be considerably lower, due to its lower alloy content, and we estimate it at $0.80 per pound in large volume. The resulting increase in cost of 0.40 cents per pound compared to low-carbon steel, multiplied by the 8.5 ounce weight of the muffler, gives an increase in material cost of $0.23 per piece (Table 52).

Table 52: Incremental variable costs for hand-held equipment equipped with catalyst.

	Heat Shield	**Muffler**
Process	Stamping	Stamping
Material	L.C. Steel	Alloy-Steel
Weight (lb)	0.313	0.531
Wgt+10%Scrap	0.344	0.584
Material cost $/lb	0.40	0.40[1]
Material Cost ($/part)	0.138	0.234
Labor minutes	1	0
Labor cost $/hr	15	15
DL Cost $/part	0.25	0.00
Overhead @40%	0.10	0.00
Total cost/part	0.35	0.00
Total equip. cost/part	**0.49**	**0.23**

[1] Incremental cost compared to existing material.

The higher muffler temperature will require a change in the thermal design of the equipment as well. Presently, a single metal muffler cover serves as a heat shield to prevent direct contact with the hot muffler. Based on practices used with catalytic converters in two-stroke motorcycles, we expect that manufacturers would add a second heat shield around the muffler cover. This would require design changes in the air cleaner cover and the fan cover assembly as well, to accommodate the increased size of the muffler/heat-shield assembly and to provide adequate cooling air to this assembly. The additional heat shield is assumed to be stamped out of low-carbon steel (since its temperature is less than that of the muffler, high-temperature steel is not required). The weight of the heat shield would be similar to that of the present muffler cover. The resulting variable manufacturing costs are also shown in Table 52. The added assembly labor to attached the heat shield would amount to about $.175, giving a total increase in the variable manufacturing cost of $0.90 (Table 53).

The fixed costs involved in modifying hand-held equipment models for catalytic converter use would include about one year of engineering labor and testing to ensure safe design of the high-temperature components. Testing and related costs are included under "other engineering". Significant safety-related changes to consumer manuals and documentation would also be needed.

The costs of the needed training and documentation changes are estimated at $100,000, which is intermediate between the costs for a major engine change ($500,000) and those of a technical support bulletin ($20,000) (Honda, 1996). Tooling costs would include new injection molds for the air cleaner cover and fan housing cover, and new stamping dies for the heat shield, muffler cover, and the three components of the muffler itself. Detailed cost estimates are shown in Table 54. Setup costs would include the changes needed in the assembly line, jigs, handling equipment, etc. to accommodate the added components and assembly operations.

Table 53: Incremental variable equipment cost for adding catalytic converter to hand-held equipment.

	Cost/ Piece	Pieces/ Engine	Total
Parts Cost			
Heat Shield	0.49	1	0.49
Alloy-Steel Muffler	0.23	1	0.23
Total Parts Cost			0.72
Added Assembly Labor			
Labor minutes			0.5
Labor Cost $/hr			15
Direct Labor $			0.125
Overhead @40%			0.05
Total Labor + OH			0.175
Total Added Variable Equipment Manufacturing Cost			0.90

Since the heat shield would be an added component, it would require an additional stamping press capacity to produce it. We estimate the press cycle time at 30 seconds, based on typical values (Amstead, Ostwald, and Begemand, 1976). Allowing for two shifts, and seven hours of production per shift, this is equivalent to about 1500 parts per shift. Thus, 400,000 parts per year for a high-volume line (case 1) would require all of the capacity of one press, running two shifts, while 90,000 parts per year for a low-volume line (case 2) would require about 25% of one press's capacity (we assume that the remaining capacity would be used on other engine lines). A 50-ton stamping press costs about $50,000 (Chew, 1996), so we assessed machine tool costs of $50,000 for the high-volume case, and $15,000 for the low-volume case (the latter allowing for some loss of production due to die changes between runs of different parts).

A summary of hardware/assembly costs, and fixed costs to modify various handheld equipment (e.g., trimmer, chainsaw, blower) to add catalytic converters is given in Table 55.

Table 54: Estimated equipment fixed costs for handheld engines with catalyst.

	Case 1	Case 2
Engineering Costs		
Engineering labor (person year)	1	1
Engineering labor + OH	100,000	100,000
Number of Tests	0	0
Test Cost ($)	250	250
Testing costs	0	0
Other engineering	50,000	50,000
Total Engineering	150,000	150,000
Technical support		
Training/Tech. Pubs	100,000	100,000
Tooling Costs		
New Injection Molding Dies		
Air Cleaner Cover	5,000	5,000
Fan Housing Cover	20,000	20,000
Muffler Cover	5,000	5,000
Heat Shield	5,000	5,000
Muffler, Top	5,000	5,000
Muffler, Bottom	5,000	5,000
Muffler, Baffle	5,000	5,000
Setup changes	40,000	40,000
Total tooling	90,000	90,000
Total Engine-Specific	340,000	340,000
Amortized over 5 yrs	87,411	86,280
New Machine Tools	50,000	15,000
Amortized over 10 yrs	7,791	2,286
Total Fixed Cost/Yr	95,202	88,566
Annual Production	400,000	90,000
Fixed cost/engine	0.24	0.98

Table 55: Summary of hardware/assembly and fixed costs to modify handheld equipment to add catalytic converters

	Cost ($/unit)	
	Case 1	Case 2
Hardware/Assembly	0.90	0.90
Fixed Costs	0.24	0.98

11. USER COSTS

This chapter addresses user costs associated with using a modified engine. The user costs consist of the incremental costs associated with fuel saving and maintenance.

11.1 Fuel Cost Savings

Engines designed to meet Phase 2 emission regulations will have the added benefit of decreased fuel consumption, leading to decreased lifecycle fuel costs to the consumer.

For engines used in non-handheld equipment, three pollution control measures are studied: (1) improved side-valve technology, (2) improved overhead-valve technology, and (3) conversion from side to an overhead-valve system. Improved side-valve design is estimated to reduce fuel consumption by 5-10 percent. This fuel range of decreased fuel consumption is consistent with a technical study that measured a 6.4 percent fuel reduction with improved side-valve design (Xia and Jin, 1991). The improved design will burn fuel more completely and burn less fuel while maintaining power output similar to the non-optimized design.

Improved overhead-valve engines incorporate many of the same changes as improved side-valve engines. Therefore, it is reasonable to assume a similar fuel consumption savings of 5-10 percent.

The fuel savings associated with converting from side to overhead-valve design are more significant than those of the improved designs described above. Overhead-valve engines are inherently cleaner burning than side-valve designs. Compared to side-valve engines, overhead-valve engine combustion is more complete, emitting fewer hydrocarbons in the form of unburned gasoline. This results in increased fuel economy. Engine manufacturer literature suggest 30-40 percent fuel savings and an estimate by one equipment manufacturer (John Deere, Conversation, September, 1996) was between 25 and 50 percent fuel consumption reduction. Thus, we assumed 35 percent.

For engines used in handheld equipment, three technologies are considered:
(1) improved two-stroke design (stratified charge), (2) improved two-stroke with catalyst, and (3) two-stroke to four-stroke conversion. The estimate of fuel savings for improved two-stroke design is 15-20 percent based on the relationship between emission reduction and fuel reduction. The addition of a catalyst should not affect the fuel savings on an improved two-stroke. For two to four-stroke conversion, Ryobi is currently the only company that currently markets a handheld four-stroke engine. Four stroke designs are inherently cleaner burning and notably more fuel

efficient than two-stroke designs. Ryobi estimates a fuel savings of 30 percent with two to four-stroke conversion.

Table 56 and Table 57 present expected savings for class I non-handheld engines for commercial and residential use, respectively. The data for average engine lifespan, average annual use, average engine horsepower, and baseline fuel consumption rate used based on a 1990 CARB study (ARB, 1990).

To determine the fuel consumption rate of the modified engine, the baseline fuel consumption rate was multiplied by the fuel saving percent. To determine the lifetime fuel cost for an unmodified engine (second row from bottom), the baseline fuel consumption rate was multiplied by the average lifespan, the average usage, the average horsepower and the price of gasoline get the baseline lifetime fuel cost. Then, to determine the lifetime fuel cost for a modified improved engine (third row from bottom), the improved fuel consumption rate (as determined above) was multiplied by the average lifespan, the average usage, the average horsepower and the price of gasoline get the baseline lifetime fuel cost. The resulting lifetime fuel savings (bottom row) was determined by subtracting the improved lifetime fuel costs from the baseline lifetime fuel cost. In these calculations, the price per gallon was $0.765 which was the refinery price to endusers excluding federal and state taxes. The price was the average for 1995 from the Energy Information Administration Petroleum Marketing Monthly, September 1996. Also, a gasoline density of 6.25 pounds per gallon was used to determine the fuel consumption on a per gallon basis.

The tables show that most of the fuel savings are in the commercial applications because of the longer lifetime use hours than residential applications. The largest savings were $220 from the side-valve to overhead-valve conversion.

Table 58 and Table 59 detail cost savings for typical handheld engines (classes III, IV, and V). The data for average engine lifespan, average annual use, average engine horsepower, and baseline fuel consumption rate used in Table 58 and Table 59 were based on a 1990 CARB study (ARB, 1990).

Table 56: Commercial Class I Non-handheld Lifetime Fuel Cost Savings by Engine Modification

Commercial Non-Handheld	Improved Side Valve	Improved Overhead Valve	Conversion Side Valve to Overhead Valve
Average Lifespan (yrs)	3	3	3
Average Usage (hrs/yr)	320	320	320
Average Horsepower	4	4	4
Baseline SV/OHV Fuel Consumption (gal/hp-hr)	0.22 for SV	0.145 for OHV	0.22 for SV
Fuel Savings %	7.5%	7.5%	35%
Improved Fuel Consumption (gal/hp-hr)	0.2	0.135	0.145
Improved Lifetime Fuel Costs ($)	$597	$394	$426
Baseline Lifetime Fuel Cost ($)	$646	$426	$646
Lifetime Fuel Savings ($)	$ 49	$ 32	$220

Gasoline price was $0.765 per gallon which was the average refinery price to enduser for 1995; source from Energy Information Administration
Source: Baseline fuel use data provided by 1990 CARB study "California Exhaust Emission Standards and Test Procedures for 1994 and Subsequent Model Year Utility and Lawn and Garden Equipment Engines", December 1990.

Table 57: Residential Class I Non-handheld Lifetime Fuel Cost Savings by Engine Modification

Residential Non-Handheld	Improved Side Valve	Improved Overhead Valve	Conversion Side Valve to Overhead Valve
Average Lifespan (yrs)	7	7	7
Average Usage (hrs/yr)	20	20	20
Average Horsepower	3.5	3.5	3.5
Baseline SV/OHV Fuel Consumption (gal/hp-hr)	0.22 for SV	0.145 for OHV	0.22 for SV
Fuel Savings %	7.5%	7.5%	35%
Improved Fuel Consumption (gal/hp-hr)	0.2	0.135	0.145
Improved Lifetime Fuel Costs ($)	$76	$50	$54
Baseline Lifetime Fuel Cost ($)	$82	$54	$82
Lifetime Fuel Savings ($)	$ 6	$ 4	$28

Gasoline price was $0.765 per gallon which was the average refinery price to enduser for 1995; source from Energy Information Administration
Source: Baseline fuel use data provided by 1990 CARB study "California Exhaust Emission Standards and Test Procedures for 1994 and Subsequent Model Year Utility and Lawn and Garden Equipment Engines", December 1990.

Table 58: Commercial Handheld Lifetime Fuel Savings by Engine Modification.

Commercial Handheld	Improved Two-Stroke (either improved scavenging or stratified scavenging)	Two-Stroke to Four-Stroke	Improved Two-Stroke with Catalyst
Average Lifespan (yrs)	2.2	2.2	2.2
Average Usage (hrs/yr)	261	261	261
Average Horsepower	3	3	3
Baseline 2- Stroke Fuel Consumption (gal/hp-hr)	0.22	0.22	0.22
Fuel Savings %	17.5%	30%	17.5%
Improved Fuel Consumption (gal/hp-hr)	0.18	0.15	0.18
Improved Lifetime Fuel Costs ($)	$235	$200	$235
Baseline Lifetime Fuel Cost ($)	$285	$285	$285
Lifetime Fuel Savings ($)	$ 50	$ 85	$ 50

Gasoline price was $0.765 per gallon which was the average refinery price to enduser for 1995; source from Energy Information Administration
Source: Baseline fuel use data provided by 1990 CARB study "California Exhaust Emission Standards and Test Procedures for 1994 and Subsequent Model Year Utility and Lawn and Garden Equipment Engines", December 1990.

Table 59: Residential Handheld Fuel Cost Savings by Engine Modification.

Residential Handheld	Improved Two-Stroke (improved scavenging or stratified scavenging)	Two-Stroke to Four-Stroke	Improved Two-Stroke with Catalyst
Average Lifespan (yrs)	5	5	5
Average Usage (hrs/yr)	9.5	9.5	9.5
Average Horsepower	1.5	1.5	1.5
Baseline 2-Stroke Fuel Consumption (gal/hp-hr)	0.22	0.22	0.22
Fuel Savings %	17.5%	30%	17.5%
Improved Fuel Consumption (gal/hp-hr)	0.18	0.15	0.18
Improved Lifetime Fuel Costs ($)	$10	$ 8	$10
Baseline Lifetime Fuel Cost ($)	$12	$12	$12
Lifetime Fuel Savings ($)	$ 2	$ 4	$ 2

Gasoline price was $0.765 per gallon which was the average refinery price to enduser for 1995; source: Energy Information Administration
Source: Baseline fuel use data provided by 1990 CARB study "California Exhaust Emission Standards and Test Procedures for 1994 and Subsequent Model Year Utility and Lawn and Garden Equipment Engines", December 1990.

11.2 Lifecycle Maintenance Savings

Improved side and improved overhead-valve designs, and improved two-stroke designs will likely have maintenance costs slightly lower than the original unmodified engines. This decrease in maintenance costs is due to the improved design allowing less oil into the combustion chamber. This leads to less carbon being deposited in the combustion chamber and decreases engine oil consumption. Also, class I side-valve improvements will result in less carburetor fixes. Commercial users would be more likely to notice such minor reduction in maintenance costs, because their more intensive equipment use leads to shorter maintenance intervals. More dramatic differences in maintenance costs are associated with a change in engine technology, such as converting from a side to overhead-valve configuration.

Overhead-valve engines have significantly lower maintenance costs than comparable side-valve designs (John Deere, Conversation, September, 1996). The merits of overhead-valve designs for both class I and class II engines include increased engine life (e.g., valve life), less frequent replacement of parts, and longer intervals between maintenance. The oil service costs provided by John Deere in Table 60 demonstrate these merits for premium tractor equipment. In this case, the air and liquid-cooled overhead-valve designs decrease maintenance costs per hour by 66 and 90 percent respectively from side-valve designs. The two major maintenance items considered are oil replacement and valve adjustment. These maintenance practices are undertaken more often by commercial engine users. Commercial users run their engines for much longer periods of time, and do so more frequently. The maintenance intervals prescribed by the manufacturer are based on hours of service. Residential users may not undertake maintenance as consistently as commercial users, and do so less often if proper service intervals are observed.

Table 60: Oil service costs for tractor engines.

Engine Design	Oil Replacement Interval (hrs.)	Expected Equipment Life (hrs.)	Lifetime Oil Service Cost (1)	Oil Service Cost, per 750 hours (2)
Side-valve	25	750	$ 1,200	$ 1,200
Overhead-valve, Air Cooled	50 - 100 (assume 75)	1,500	$ 800	$ 400
Overhead-valve, Water Cooled	250	3,500	$ 560	$ 120

Source: John Deere
(1) - Oil change cost - $40/service (Wicks Repair, Alexandria, VA)
(2) - For comparison purposes, developed cost for 750 hours

Valve train adjustments are generally required once over the lifetime of an engine. This service costs approximately $50 (Wicks Repair, Alexandria, VA). For a premium side-valve engine, the service is required within the first 100 hours of use. Premium overhead-valve engines require the service in the first 1,000 hours of use (John Deere, Conversation, September, 1996). Users of commercial equipment with side-valve engines will have the cost and inconvenience of servicing their engines much sooner than users of commercial equipment with overhead-valve engines. Perhaps, because of the long time before an overhead-valve engine needs adjusting, the commercial user of overhead-valve equipment may not even incur the cost of valve readjustment. Similarly, many residential users may not use an overhead-valve engine to the point where it requires a valve adjustment, thereby avoiding the cost and inconvenience of the service. A residential user would almost certainly use a side-valve engine to the point where it requires an adjustment.

For handheld equipment engines, improved two stroke engine will reduce oil consumption and minimize oil and carbon deposits in the chamber. This results in probably some, but not a significant reduction in maintenance. Similarly, the engine with stratified charge and a catalyst will have a small reduction of maintenance due to the stratified charge design. Finally, the conversion of two to four stroke design may result in somewhat additional maintenance reductions than the other improvements to the handheld engines because of the reliability of four stroke designs.

12. CONSTRAINTS

This chapter explores the sensitivity of the engine incremental cost data (provided in the bottom up engine analyses Parts I and II) by considering other possible constraints that may affect the cost of the engine. It addresses rule-related constraints, manufacturer-related constraints, and technology-related constraints. We focused on the six technologies studied in this report. There is some uncertainty in determining the influence of these constraints on the estimated costs per engine because it is not clear what types or combinations of technology modifications the manufacturers will use to achieve emission reductions. It is also not clear which engine families will be modified with the different technologies. This chapter addresses these constraints through general discussions, by making certain assumptions to enable quantitative analysis, by characterizing the engine manufacturers data, and by providing various illustrative examples.

12.1 Rule-Related Constraints

This section describes how some of the implementation features of the Phase 2 regulations may affect the cost of the engines. The implementation features that could affect engine costs include the lead time provided to meet the Phase 2 regulations and the phase-in schedule which determines the percentages of engines that must comply each year with the emission regulations. For handheld engines, the anticipated implementation is for model year 2002 with a four year phase period as follows:

Model Year	Percent of Production
2002	20
2003	40
2004	70
2005	100

For non-handheld engines, the phase in period has not been defined; however, for the purposes of this analysis of rule-related constraints, we have assumed the following phase-in period for engines that need major design changes (i.e., conversion of class II side-valve to clean durable OHV) to comply with the emission standards.

Model Year	Percent of Production
2001	50
2003	75
2005	100

The effects of rule-related constraints (e.g., lead time) on the costs of engines depends on a number of different factors including:

- the assumption about the start time for manufacturers (when Phase 2 regulations are promulgated or when manufacturer is informed of/or agrees to emission reduction levels);
- level of experience/preparation of the manufacturer (e.g., advanced R&D) to implement engine changes;
- manufacturer resources;
- number of engine families/models that need to be modified;
- the timing for typical replacement/retiring of dies, tooling equipment, training manuals, training, etc.
- ability of the manufacturer to use/adapt capital equipment to manufacture the modified engine;
- the type or combinations of engine modifications necessary to meet emission levels;
- industry structure to integrate engine with equipment; and
- extra lead time to develop certain newer technologies.

The following topics regarding rule-related constraints are covered: start time, lead time, possible cost impacts of phase-in schedule, factors that affect the early retirement of equipment and tooling, possible early retirement costs, and strategy/challenges to meet phase-in schedule.

Start Time

A cost analysis of rule-related constraints also depends on the start of the lead time for the Phase 2 regulations. For this analysis, we assume that lead time for complying with the Phase 2 regulations starts in mid 1997, the official date of the expected final rulemaking. This start date is also reasonable because the Statement of Principles was completed in May 1996 for handheld engines and the SOP for non-handheld engines is currently being drafted.

Lead Time

We conducted a brief evaluation to determine if adequate lead time is provided to comply with the Phase 2 regulation. Presumably, some manufacturers are already planning engine modifications to comply with the CARB 1999 Tier II emission regulations on utility engines. EPA Phase 2 will have an implementation date several years after the CARB implementation date.

The typical product development cycle for small engine and equipment includes several steps including concept development, feasibility, preliminary design, final design, qualification, pilot production, and production. Varying amounts of lead time will be required depending on the level of redesign/replacement required, the emission levels that need to be achieved, and the durability and performance requirements of the engine. Also, several layers of testing may be required for system integration. The projected lead-time for a single engine family is typically two to four years. (Technology Task Group, September 1995.) The lead time necessary for specific engine modification technologies is another area of great disagreement.

For adding a catalyst to two-stroke handheld engines, scavenging losses must be reduced. Industry has made some progress in minimizing the other problems associated with packaging, high exhaust and surface temperature, durability of the catalyst because of excessive heat, vibration, and possible contamination. For example, Husqvarna had recently announced (Husqvarna Newsbrief, 1996) development of an advanced two-stroke engine that reduces scavenging losses and that features a low temperature catalyst. This technology will be available on a range of Class IV trimmers, edgers, hedge trimmers and blowers in 1997. Also, chainsaws and mowers have been equipped with catalytic converters in Europe, however, Europe does not have the temperature standards from the U.S. Forest Service. CARB asserts that catalysts will be ready on utility equipment by 1999, the implementation year of the Tier II regulations. In contrast, the Power Equipment Manufacturers Association (PEMA) has asserted in comments to CARB (CARB, January 1996) that a catalyst for handheld is not ready until formidable issues are addressed (e.g., heat management) and catalyst will not be feasible until various techniques are perfected to reduce scavenging losses. PEMA states that more lead time is needed. In terms of making a lead time assumption for this study, we believe that because some additional R&D is needed across the engine manufacturing industry, lead time for production may be 3-4 years for one engine family. Given a start time of mid 1997 and an initial phase-in date of 2002, the manufacturer would have just sufficient time to add a catalyst to one or more of its engine models.

Concerning two to four-stroke conversion, Ryobi's development of a lightweight four-stroke engine for handheld applications provides some guidance on lead time. Ryobi generally developed their four-stroke handheld engine over a period of about 6-8 years (Ryobi Newsbrief, 1995). However, acceptance and spreading of this technology throughout the industry is an issue. Ryobi has signed an agreement with Toro to produce four-stroke trimmers and is discussing licensing the technology to other manufacturers. The Ryobi engine, however, will not be able to be used in certain multiposition applications (e.g., chainsaw). Honda has recently developed a four-stroke handheld that could be used in multiposition applications. PEMA points out that more lead time is needed because the Ryobi engine may not meet certain emission reduction levels (e.g., Tier II) and confirms the problem of using a Ryobi-type engine in chainsaws. In terms of making a lead time assumption, we believe that because of the newness of the two to four-stroke technology, a lead time of 4-5 years for production of one engine family will be needed. Given a start time of mid 1997 and an initial phase-in date of 2002, the manufacturer may not have sufficient time to design and produce a four-stroke engine in the first year of the Phase 2 implementation unless efforts started before mid 1997.

In terms of conversion of non-handheld engines from side-valve to overhead valve, most manufacturers produce some part of their engine lines with overhead valve. The technology is widely available and depending on the final emission standards, OHV may be used more extensively. In terms of making a lead time assumption, we believe that because the clean durable OHV technology is accessible and in use by many non-handheld manufacturers, a lead time of 2-3 years for one engine family is reasonable. Given a start time of mid 1997 and an initial phase-in date of 2001 for non-handheld equipment (one year before handheld), the manufacturer should have adequate time to design and produce one or more lines of OHV engines. However, assuming the phase-in compliance schedule is 100 percent production volume or class I engines and 50 percent production for class II engines, the manufacturers cannot wait to convert their lines unless a substantial portion of their engines already comply with the Phase 2 emission standard.

It is important to note that for all of the engine modifications discussed above, progress in the development/production process can be concurrently applied to additional engine families.

Potential Cost Impacts of Phase-In Schedule

There are a couple cost impacts that the proposed rule phase-in schedules may have on engine manufacturers. First, if engine manufacturers can wait until equipment need replacing before converting engine models in response to a rulemaking, they can avoid losses associated with premature retirement of capital equipment. If they cannot wait, and have to discard equipment such as dies that have remaining useful life, manufacturers lose a percentage of the capital equipment cost commensurate to the percentage of remaining useful life of the production equipment. Secondly, some manufacturers may have to convert a large percentage of the number of engine models to accommodate the proposed phase-in schedules. In this instance, manufacturers may incur early and significant equipment and labor costs to accomplish model conversion in the phase-in schedule.

Factors that Affect the Early Retirement of Engine Manufacturing Equipment and Tooling

The likelihood of needing to discard equipment with useful life is a function of equipment usage. The most important equipment that may need to be retired are the dies. Dies generally have a useful life of 100,000 presses, which produce at least 100,000 engines. Manufacturers with large volume engine lines may have dies that can produce as many as 6 engine parts per press (Briggs and Stratton, September, 1996) or 600,000 engine parts per die life. Dies that are used to produce a large number of engines per model last a short time whereas dies used in the production of low volume engine models last longer. For example, dies used in the production of a high-volume class I engine model with 1.2 million engines annually are replaced at least twice and at most twelve times per year. Dies used for an engine model with 35,000 engines produced per year however, are replaced every three years. Lines smaller than 35,000 engines will have an even longer years of service.

The maximum amount of time before dies are replaced will influence the likelihood of needing to retire capital equipment (e.g., dies) early. The impact is discussed for high, intermediate, and low volume manufacturers.

High Volume Manufacturers. Manufacturers with large market share generally produce engine models with greater unit volume than medium and small volume manufacturers. These dominant high-volume engine models for the large handheld or non-handheld manufacturers produce at least 100,000 engines annually and likely require die replacement at least annually. In the context of a phase-in schedule, these high-volume engine lines are unlikely to face any problems of early retirement losses because the dies are replaced so frequently (i.e., several times a year). Also, because the manufacturer will likely convert the high-volume lines first to comply with the phase-in regulation, the manufacturer will suffer no early retirement loss. In addition, any small or intermediate volume lines in the large manufacturer can be converted at the manufacturers discretion (i.e., when the die lifetime use is complete) to avoid early retirement costs from these lines. Finally, any retirement costs will be small when averaged over the total large production volume of engines.

Intermediate and Low Volume Manufacturers. When Phase 2 emission limits are established in mid 1997, medium and low volume manufacturers will likely consider modifying engine models that have dies with no remaining useful life (i.e., dies that have performed 100,000 presses) by the first year of implementation (e.g., year 2002 for handheld and 2001 for non-handheld). For small volume manufacturers, losses from early retirement of dies is spread over a significantly smaller number of total engines produced (i.e., loss per engine is far greater), which makes this cost more significant. In addition, small manufacturers have far fewer engine models to convert (generally five or fewer engine models), which means that there are fewer combinations available that accomodate the phase-in schedules. Models that are ready for die replacement may not constitute enough of total production to achieve compliance for some manufacturers, forcing these manufacturers to scrap dies prematurely in order to comply. Small volume manufacturers would prefer to wait until dies for all engine models have performed 100,000 presses before conversion. Medium volume manufacturers have similar conversion concerns, but generally have greater flexibility through more engine models and quicker die replacement schedules.

Ultimately, the likelihood of needing to discard production equipment with remaining useful life depends a complex set of variables including engine volume size, the lead time required for the engine modification, the implementation year of the regulation, and the phase-in schedules.

Possible Early Retirement Costs

The type of engine modification will impact the retirement costs. More extensive modifications typical of SV to OHV and two to four-stroke will potentially incur the most retirement costs.

SV to OHV Conversion of Non-Handheld Engines. In the SV to OHV conversion, there is concern about the need to retire SV capital equipment. Although machine tooling equipment originally used for SV can be adapted for use in manufacturing OHV (Briggs and Stratton conversation, 1996), however, the dies for the SV will have to be retired. These dies typically cost $25,000 each for a main part (e.g., cylinder head, cylinder block, crankshaft, piston), and $15,000 each for other parts (e.g., connecting rod). For the SV to OHV conversion, the side-valve capital equipment that may have to be retired early per engine model include dies for cylinder block, cylinder head, connecting rod, piston, and crankshaft. Thus, the maximum total cost to the manufacturer for retirement of the dies is $115,000 per engine line. If the dies used in SV engine production have two years of remaining useful life out of three total years of useful life, manufacturers lose two thirds of $115,000, or $76,000). Using this loss rate and given a hypothetical medium sized non-handheld manufacturer with approximately 15 engine models, each producing 35,000 engines per year, the total retirement cost would be $1.14 million over three years. This would be equivalent to about $0.7 additional cost per engine (based on three years total sales) as a result of early retiring of capital equipment over a three year period.

Two to Four-Stroke Conversion. To convert a two to four-stroke handheld engine, the two-stroke manufacturing capital equipment that may have to be retired early per engine model include a die for cylinder head/block ($40,000), die for piston ($15,000), die for carburetor ($60,000), die for connecting rod ($15,000), die for crankshaft ($25,000), and die for crankcase ($40,000). The total is $195,000.

Strategy/Challenges to Meet Phase-in Schedule

Most small engine manufacturers, whether big or small, will have a few engine lines that will dominate the manufacturer's total engine production. Unless a large percent of the engine production already meets the emission regulations by the time they are implemented, these dominating engine lines would be expected to be converted first, in advance of the regulations to meet the compliance phase-in.

The proposed phase-in schedule for non-handheld manufacturers is faster and more dramatic in the first year of implementation than the handheld. By 2001, class II non-handheld manufacturers must have 50 percent of production in compliance. Generally, SV to OHV conversion for class II engines may be necessary to achieve compliance. This first year compliance phase-in is in part based on the assumption that a certain percentage of non-handheld engines are already overhead valves and will not require conversion. Nonetheless, this phase-in could pose problems for some manufacturers of Class II non-handheld engines, which will convert many engine models from side valve to overhead valve. Table 61 illustrates the percent of claaa II manufacturers' production that was side valve in 1993 according to the Power Systems Research database. The percentages may have changed in the last several years. The table shows that manufacturers with the largest market share (58 percent - 2 percent of total Class 2 engine production) have significant percentages of production that need to be converted from side valve to overhead valve (24 percent - 100 percent). These manufacturers, however, produce many models (22 - 39 models), of which a few would likely need new dies before they must be converted. Also, large volume manufacturers tend to have several other models to choose from to comply with the phase-in schedules. Smaller manufacturers that have a high percentage of side valve engines that will require conversion will have significantly fewer engine models (in some cases only one model). These manufacturers need to convert 50 percent of production by the year 2001, which may likely require early retirement of dies and a loss on capital investment.

Table 61: Characterization of Class II Non-handheld Engine Manufacturers.

Percent of Total Class II Production for Different	Number of Engine Models	Percent Side Valve Production (Representing Percent of Manu-
58.10%	39	87%
11.97%	19	24%
9.67%	26	79%
9.02%	22	89%
4.64%	27	85%
1.62%	22	100%
1.45%	3	0%
1.43%	15	0%
0.47%	1	0%
0.43%	4	76%
0.29%	1	100%
0.24%	1	0%
0.22%	1	0%
0.14%	1	0%
0.12%	2	57%
0.10%	2	0%
0.07%	1	100%
0.03%	4	100%

Source: *Power Systems Research, 1993.*

12.2 Manufacturer-Related Constraints

This section describes the constraints on the engine manufacturing sector to modify the engine (e.g., convert SV to OHV). The constraints are evaluated in terms of the profile of the engine manufacturing sector which includes the market dynamics between manufacturers (e.g., big/small, general/specialty) and the engine family/model structure within these manufacturers. The overall constraints are stated in terms of their general effect on the costs of producing the modified engines.

Choice of Technology to Meet Emission Standards

Manufacturers could choose any of the six engine modification technologies evaluated in this study or perhaps other technologies to meet anticipated Phase 2 emission standards. The type of technology chosen will certainly influence the compliance costs. Manufacturers may choose different modification methods to comply. Some modifications will be less expensive than others (see bottom-up engine analysis Parts I and II for the six technologies studied). Some manufacturers already manufacturer engines that use such technologies (e.g., OHV) and will meet Phase 2 emission standards without additional costs. It might be expected that certain manufacturers that primarily serve the consumer equipment market (i.e., Briggs and Stratton) where engine/equipment price is a critical factor may pursue the less expensive modifications. The active competition between Briggs and Stratton and Tecumseh in the consumer equipment market will support this logic to pursue least expensive options. Other manufacturers that produce specialty engines (e.g., Teledyn-Wisc) or premium engines (e.g. Kohler) may choose to invest in more expensive or extensive technologies that enhance the performance or premium reputation of the engine/equipment as well as meeting the emission standards. The engine modification pursued by the manufacturer (and therefore the cost) may be influenced by other reasons including the motivation to pursue efforts that build on past and existing R&D efforts, on the assets of the manufacturer to pursue new and perhaps unproved technologies, on the manufacturer's policy and culture concerning changes to the engine, and on manufacturer knowledge about the application of the engine in the equipment and the preferences by the equipment manufacturer and the consumer. Assets for R&D may not be entirely a function of market share, but may also be a function of the wealth of a parent company or its success in other markets (e.g., Honda).

Manufacturer Size and Engine Cost

Given the same engine modification undertaken by different manufacturers, cost of the engine modification can still differ. The size of the manufacturer as expressed in number of engines produced and sold is one factor that will influence the cost of the engine modification to the manufacturer.

Non-Handheld Manufacturers. The non-handheld category is largely composed of two engine manufacturers that dominate. Briggs and Stratton and Tecumseh account for over 90 percent of all class I engines and over 74 percent in class II (all market share percentages from PSR ENGINDATA database). Two medium-sized manufacturers (e.g. Honda, Lawnboy/Toro) together make up 9 percent of the class I engines and three medium-sized manufacturers (e.g., Kawasaki, Kohler, Onan) together make up over 20 percent of the class II engines. The rest of the manufacturers of either the class I or class II engines represent a very minor part of the market. All of the six engine modification studies in this report will require additional parts. Some of the parts will be provided by suppliers and others may be produced by the manufacturer. For any specific engine modification, it is anticipated that the Briggs and Stratton and Tecumseh will be able to get large-volume discounts from suppliers and further discounts in purchasing machining tools to produce some parts in house. These large manufacturers will also receive raw material discounts (e.g., steel, aluminum) and labor efficiency savings. Companies with more modest market share will receive smaller discounts and will likely need to buy a higher proportion of additional parts from suppliers. The costs for modifying engines for small engine manufacturers will likely be significant and proportionally much higher than the increase in engine cost from medium to large engine manufacturers.

Handheld Manufacturers. For the hand-held class IV engines, the market can be characterized as a two tiered market (e.g., large and small), and therefore the engine volume factors that affect cost still apply. Class IV is dominated by Poulan, Homelite, Stihl, and Ryobi/Inertia Dynamic (representing over 90 percent of the market). In the relatively small class V, Homelite and Poulan, and Tecumseh represent over 90 percent of the market) (PSR ENGINDATA). One difference in this handheld category is that these manufacturers tend to produce both the engine and equipment. Perhaps, as compared to the non-handheld manufacturers, this industry structure to the handheld manufacturers will have closer cooperation and communication in modifying the engine and equipment and therefore, will result in comparatively lower costs to modify an engine line.

Engine Family and Engine Cost

The cost per engine will depend somewhat on the engine family/model within a single manufacturer, but when compared with other factors, the engine family/model is not expected to be a significant variable affecting the engine cost for most of the six technologies examined in study. It is expected that different size parts will be needed to modify different engine families/models. Larger parts tend to be more expensive and if produced in-house, larger parts will require more material and different stamp and die molds. In an SV to OHV conversion, each engine family will require a different master die for the cylinder head and block. It is not expected, however, that the cost of making of a master die for one OHV engine family will differ from the cost of making a master die for another OHV engine family. Different engine families/models will also require different drill/tap sizes, but the main cost associated with this is labor which would not change from engine family to engine family. For handheld equipment engines that use a catalyst, the cost per engine could differ somewhat depending on the engine family. Catalyst materials are expensive and larger engines require larger amounts of catalyst, however, the overall difference in cost between the smallest to the largest handheld engines is not expected to be significant.

Application and Engine Cost

Engines are used in a variety of equipment and applications. It is expected that some changes to the equipment may be needed to accommodate the modified engine technologies. For example, it is expected that for all handheld applications, engines with catalysts will need a heat shield. A further description of these types of changes and their associated costs are outlined in the bottom-up engine analyses Parts I and II. Additionally, the cost of producing a modified engine itself for a variety of equipment applications is not expected to changes costs. For example, a mounting bracket on an OHV engine intended for use on a lawnmower is not expected to cost more than a mounting bracket on an OHV engine intended for use on a snowblower.

Transition Costs for Manufacturers

As discussed under rule-related constraints, manufacturers could experience additional costs per engine from having to prematurely retire capital equipment (primarily dies) that cannot be used to manufacture the modified engine. Because these retirement costs are dependent on the number of engine families/models and not on the number of engines produced, the cost per engine associated with the retired dies would be larger for manufacturers that make a small number of engines per engine family. For engine manufacturers that embark on the engine modifications early, market share loss to other manufacturers could be an important short term loss. For example, an engine manufacturer that switches their engine line from SV to OHV may lose business from an equipment manufacturer that still wishes to purchase SV engines. This loss to manufacturers could be in the tens of millions, however, the manufacturers may not pass on these costs immediately because the playing field should level out when all manufacturers have to comply with the emission reduction regulations.

Costs to Participate in California Market

Manufactures that are heavily involved in the California market may have to pursue more expensive technology modifications in order to comply with stringent Tier II emission standards. Such manufacturers would include Briggs and Stratton and Tecumseh. However, if the market for both California and the rest of the U.S. is large, a manufacture such a Briggs and Stratton could consider developing separate engine families/models that meet the California Tier II and the Phase 2 emission standards, respectively.

12.3 Technology-Related Constraints

There are technological constraints associated with the engine modifications considered in this study. The technological constraints discussed below include issues of technical feasibility, production feasibility, and market penetration.

There are some limits to the technical feasibility of applying the engine modifications to some engines and equipment to meet phase 2 emission standards. Some of these are mentioned in the above section on rule-related constraints and in Part 1 and Part 2 of the study.

On the hand-held side, the constraints on using catalysts include safety concerns due to the heat generated. Applying a catalyst to a two-stroke engine without reducing scavenging losses will create great heat. Equipment that emit this heat will not comply with various temperature regulations (e.g., OSHA and USDA National Forest Service) and other requirements. In Europe, catalysts are used on handheld equipment because of less stringent temperature requirements. In the U.S., no examples are yet available which show high emission conversion efficiency and low temperatures on handheld equipment. However, a number of methods are being explored to reduce temperatures below a safe limit (Technology Task Group, September, 1995). These include heat shield (e.g., guard), stratified charge, and fuel scavenging through direct fuel injection, air scavenging or enleanment. One solution may be to use a lower efficiency catalyst on a smaller size two-stroke. A recent development by Husqvarna may have effectively addressed the temperature issue (see above discussion in rule-related constraints). The temperature issue also affects the durability of the engine and equipment. The catalyst will also add weight to the weight-sensitive handheld equipment. However, CARB states (CARB, 1994) that a catalyst system may only add one pound to the equipment.

Also of concern for a catalyst system is the need for exhaust hardware changes to prevent flaming out of exhaust, engine control to maintain correct air/fuel ratio, maximum conversion efficiency of emissions, vibration concerns, and closed loop feedback. According to CARB (CARB, January, 1996), there are several possible solutions to these issues that can make two-stroke catalyst engines feasible by 1999, well in advance of the 2002 EPA Phase 2 emission standards. Six engine families have been certified for CARB Tier I regulation. Numerous efforts, past experience, and recent accomplishments in this area of catalyst technology would seem to suggest that 2002 should give sufficient lead time to achieve emission reductions over Phase 1 levels.

There are several technical issues in converting two to four-stroke handheld engines. The basic oil splash system in four-stroke handheld does not permit multipositional use of equipment. The oil can leak. The lightweight four-stroke technology and design is relatively new (see description in rule related constraints). Additional R&D can refine this technology and perhaps address the multiposition-use issue (as possibly addressed by Honda) may necessitate an additional year of lead time. Extensive licensing of the lightweight four-stroke technology, although unlikely across the industry, may eliminate this need for additional lead time.

In the non-handheld engine sector, the conversion of SV to OHV is a known and demonstrated change. The technology conversion has few technical challenges, however, there may be some minor redesign of certain equipment to address the slightly heavier and more bulkier engine (see chapter 10 equipment cost analysis). The conversion of SV to OHV is not expected to need additional lead time based on technical feasibility issues.

The market penetration ability of the SV to the OHV will be an issue for some applications, but not for others. Particularly, the consumer SV market in lawnmowers may be difficult to penetrate. Also, some engine manufacturers that are relatively new to the OHV engine market with have to compete with more experienced OHV engine manufacturers. In addition, equipment manufacturers will need time to perhaps redesign their equipment, however, this redesing can not begin until the engine manufacturer share engine plans or when the new engines become available. Equipment manufacturers usually redesign equipment in a five year cycle so the expected lead time for market penetration might be sufficient if the engine manufacturer give advance notice of engine conversion plans to OHV. However, if the OHV engines are not made available until the year of implementation, the equipment manufacturers will not be able to redesign the equipment to be used until the second or third year of implementation.

For the two to four-stroke conversion for handheld equipment, the market penetration into equipment used in one position (e.g., edger) market should not experience technical barriers. However, the handheld market that requires multipositional capability (e.g., chainsaw, hedge trimmer) will be difficult because current four-stroke handheld technology cannot be applied to multipositional equipment. However, Honda has announced that it will introduce a small four-stroke engine for handheld application that can be used in multipositions.

The addition of catalyst to a handheld equipment may face slow market penetration because additional time is needed to redesign the equipment to handle the catalyst and heat management systems. However, because of the general vertical integration of the handheld engine/equipment manufacturers, any equipment design changes may be more effectively integrated into the equipment.

13. SUMMARY

This cost study for Phase 2 small engine regulations determined the incremental costs estimated to be incurred by engine manufacturers over the Phase 1 baseline. The study addresses small spark-ignition engines used in handheld and non-handheld equipment. A bottom-up approach was used to determine the variable hardware/assembly costs and the fixed costs associated with six engine modification technologies. For non-handheld engines, the technologies included conversion of side-valve (SV) design to overhead-valve (OHV) design, improved SV design, and improved OHV design. For handheld engines, the technologies included conversion of two-stroke design to four-stroke design, improved two-stroke, and two-stroke with catalyst.

Table 62 presents a summary of the variable and fixed costs of the various modifications for the non-handheld engines. The estimates were developed without using specific engine manufacturer data on costs. However, manufacturers did provide the technical and manufacturing process information required to make the estimates. Many other information sources were consulted for the costs. In many cases, engineering judgement was required. For non-handheld engines, three engine volume sizes - high (case 1), intermediate (case 2), and low (case 3) - based on engine data were used for the fixed costs to provide a range of estimates. Several findings appear for non-handheld engine modifications (engine classes I and II).

- improvements to existing engine design are generally less costly than major design changes
- the most costly engine modification both in terms of variable and fixed costs is the conversion of SV to OHV
- modifications that do not require variable costs (improved spark ignition in SV and improved valve timing in SV) are the least costly options
- incremental cost estimates are highly dependent on the size of the line
- for low-volume lines, the fixed costs tend to approach or exceed the variable costs
- for high-volume lines, the variable costs tend to predominate

Table 63 presents a summary of the variable and fixed costs of the various modifications for the handheld engines. For handheld engines, two engine volume sizes - high (case 1) and low (case 2) were used for the fixed costs. Several findings appear for handheld engine modifications (engine classes III, IV, and V).

- improvements to engine design are generally less costly than major design changes
- the most costly engine modification both in terms of variable and fixed costs is the conversion of two to four-stroke

Table 62 Incremental Variable and Fixed Costs for Modifications to Non-Handheld Engines

Engine Modification	Type of Cost	Case 1 (High Volume)	Case 2 (Intermediate Volume)	Case 3 (Low Volume)
SV to OHV Class I	Hardware/Assembly Fixed	9.23 0.44	9.23 1.62	9.23 8.66
SV to OHV Class II	Hardware/Assembly Fixed	Not applicable Not applicable	12.88 1.62	12.88 8.66
Improved SV (Combustion System)	Fixed	0.07	0.36	2.06
Improved SV (Spark Ignition/Timing)	Fixed	0.02	0.13	0.72
Improved SV (Valve Timing/Cam Design)	Fixed	0.12	0.51	2.27
Improved SV (Piston/Ring Design)	Hardware/Assembly Fixed	2.73 0.07	2.73 0.39	2.73 2.[illegible]
Improved SV (Manufacturing Variability)	Hardware/Assembly Fixed	0.35 0.11	0.35 0.38	0.35 1.90
Improved SV (Carburetor)	Hardware/Assembly Fixed	0.35 0.07	0.35 0.69	0.35 3.94
Improved OHV (Combustion System)	Fixed	0.09	0.53	3.05
Improved OHV (Piston, Ring Design, Bore Finish)	Hardware/Assembly Fixed	2.25 0.12	2.25 0.47	2.25 2.35

- for low-volume lines, the fixed costs tend to approach or exceed the variable costs
- for high-volume lines, the variable costs tend to predominate
- modifications that do not require variable costs (improved two-stroke scavenging) are the least costly options

Table 63 Increment Variable and Fixed Costs for Modifications to Handheld Engines

Engine Modification	Type of Cost	Case 1 (High Volume)	Case 2 (Low Volume)
Two- to Four-Stroke	Hardware/Assembly Fixed	9.93 1.73	9.93 4.09
Improved Two-Stroke Scavenging	Fixed	0.34	1.43
Improved Two-Stroke Stratified Scavenging	Hardware/Assembly Fixed	1.58 0.41	1.58 1.60
Improved Two-Stroke Scavenging with Catalyst (Ceramic Metal)	Hardware/Assembly Fixed	4.58/8.58 0.64	4.58/8.58 2.63

Further reductions from the costs estimated in this study may come from improved redesigns the engines and improved production processes. Warrantee costs to the manufacturer may al be reduced. Additionally, a learning curve may reduce variable costs for every subsequent ye of engine line production. Also, costs can be reduced because progress in modifying one engir line can be concurrently applied to additional engine families. In this study, however, these reductions were not incorporated into the cost estimates.

Equipment manufacturers will have to make a variety of changes depending on the type of engine modification. In the non-handheld equipment, various levels of changes were characterized for rear engine riders, lawn tractors, lawn and garden tractors, snowblowers, generators, and pumps. In the handheld equipment, manufacturers will incur fixed or variable costs that are no greater than one dollar per equipment unit from either adding a catalyst or from replacing a two-stroke with a four-stroke engine.

The analysis of fuel impacts showed that fuel savings was greatest for major engine modifications (SV to OHV and two to four-stroke). In commercial applications, the resulting fuel savings may significantly offset reduce the incremental costs passed on to the consumer due to modifying the engine and redesigning the equipment. Lifecycle maintenance would be reduced somewhat by all engine modifications except for the case of a catalyst added to a two-stroke (due to additional heat). The most prominent lifecycle maintenance is for SV to OHV conversion (from routine maintenance), however, this may be nullified by more expensive repairs to OHV versus SV.

Early retirement of capital equipment due to an engine modification is dependent on a complex set of variable including the rule constraints (e.g., phase-in, start time), the type of modification, the engine class affected, and the profile of the engine lines in the manufacturer. Generally, in complying with the phase-in schedule, manufacturers with mostly low-volume engine lines will be more likely to incur early retirement losses of capital equipment than manufacturers with medium and high-volume lines.

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APPENDIX A:

ELECTRONIC CONTROL SYSTEMS AND EXHAUST AFTERTREATMENT TECHNOLOGIES FOR NON-HANDHELD ENGINES

This appendix discusses in detail electronic control systems and exhaust aftertreatment technologies for non-handheld engines.

Electronic Control Systems - Electronic control technology for stoichiometric engines using three-way catalysts has been extensively developed. These systems rely on monitoring the exhaust competition to adjust the air-fuel ratio entering the combustion chamber. An automotive lambda sensor can be used for the larger of the small engines operating at, or near stoichiometric air-fuel ratios (Technology Task Group, 1995).

The main function of the computer in a feedback emission control system is to adjust the air-fuel ratio to maintain the narrow range needed by the three-way catalyst. In addition to the air/fuel ratio, modern computer control systems are also used to control many features that were controlled by vacuum switches or other devices on earlier emission control systems. These include spark timing, exhaust gas recirculation, idle speed, air injection systems, and evaporative canister purging.

The stringent air-fuel ratio requirements for three-way catalyst operation made electronic control systems necessary. However, the increased precision and flexibility of air-fuel ratio control made possible by the electronic system can greatly reduce emissions, even in the absence of a catalytic converter. Many computer control systems also have the ability to "self-diagnose" problems with the engine and control system to some extent. The capability to warn the equipment operator of a malfunction and assist the mechanic in its diagnosis may help to improve the quality of maintenance.

Exhaust Aftertreatment

A useful alternative to controlling emissions within the engine cylinder is to reduce them by subsequent treatment of the exhaust gas. This allows the combustion process within the cylinder to be optimized (within some limits) for maximum power and fuel economy, rather than for reduced emissions. The two aftertreatment technologies that have seen wide use on spark-ignition engines are air injection and the various types of catalytic converters. The use of catalytic aftertreatment allows an order-of-magnitude reduction in pollutant emissions compared to that achievable with engine-out controls alone. In addition, by reducing the need for engine-out emissions control, the use of a catalytic converter allows power and fuel economy to be improved at the same time.

Air Injection - The hot exhaust gases expelled from the cylinder of an Otto-cycle engine contain significant amounts of unburned hydrocarbons and CO. If sufficient oxygen is present, these gases will continue to react in the exhaust system, reducing the quantities of these pollutants that are ultimately emitted from the tailpipe. The reaction rate is extremely sensitive to temperature - a minimum of 600 °C is needed to oxidize hydrocarbons significantly, and a minimum of 700 °C for CO. To provide the needed oxygen under rich or stoichiometric conditions, air is injected into the exhaust manifold. In some motorcycle engines, this air is provided by a system of check valves which uses the normal pressure pulsations in the exhaust manifold to draw in air from outside.

Air injection was first used as an emission control technique in itself, and is still used for this purpose in many four-stroke motorcycle engines to meet emission requirements. Air injection can also be used with oxidizing catalytic converters, in order to ensure that the mixture entering the catalyst has λ greater than one. In vehicles equipped with three-way catalytic converters, air injection before the three-way catalyst must be avoided, to allow control of NO_x emissions. Thus, in three-way catalyst engines, air injection is used primarily during cold starts, and is cut off during normal operation.

<u>Catalytic Converters</u> - The catalytic converter is among the most effective exhaust emission control devices available. By chemically processing the exhaust to remove pollutants, the catalytic converter makes it possible to achieve much lower emissions levels than are possible with in-cylinder techniques alone. Catalytic converters require lead-free fuel, since lead from the antiknock compounds often used in gasoline forms deposits on the catalyst material. These deposits "poison" the catalytic converter by blocking the exhaust gases' access to the catalyst. As little as a single tank of leaded gasoline will significantly degrade catalyst efficiency.

Two types of catalytic aftertreatment are commonly used for automotive engines: oxidation or "two-way" catalysts and oxidation/reduction or "three-way" catalysts. Oxidation catalysts use platinum and/or palladium to increase the rate of reaction between oxygen in the exhaust and unburned hydrocarbons and CO. Ordinarily, this reaction would proceed very slowly at temperatures typical of engine exhaust. The effectiveness of the catalyst depends on its temperature, on the air-fuel ratio of the mixture, and on the mix of hydrocarbons present. Highly reactive species such as formaldehyde and olefins are oxidized more effectively than less-reactive species. Short-chain paraffins such as methane, ethane, and propane are among the least reactive hydrocarbon species, and are difficult to oxidize.

Three-way catalyst formulations use a combination of platinum and/or palladium and rhodium. In addition to promoting the oxidation of hydrocarbons and CO, these metals also promote the reduction of NO to nitrogen and oxygen. For the NO reduction to proceed efficiently, an overall rich or stoichiometric air-fuel ratio is required. The efficiency of NO_x control drops rapidly as the air-fuel ratio becomes leaner than stoichiometric. If the air-fuel ratio is maintained precisely at or just rich of stoichiometric, a three-way catalyst can simultaneously oxidize HC and CO while reducing NO_x. The "window" of air-fuel ratios within which this is possible is very narrow, however, and there is a tradeoff between NO_x and HC/CO control even within this window.

Figure 1 shows how the efficiency of a typical three-way catalyst varies as a function of air-fuel ratio. To maintain the precise air-fuel ratio required, modern gasoline cars use exhaust λ sensors (also known as oxygen sensors) with computer electronic control systems for feedback control of the air-fuel ratio. Such systems are also used on at least two BMW motorcycle models equipped with three-way catalytic converters.

In order to perform their function, the precious metals in the catalytic converter must be supported in intimate contact with the exhaust gas. The most common type of catalyst support is a single piece of ceramic (ceramic monolith) which is extruded to form numerous small parallel channels and then fired. The exhaust gases flow lengthwise through the parallel channels, which provide a very high surface area. Other types of supports include ceramic bead beds and cellular structures of high-temperature metal alloy. The latter are used primarily in situations where mechanical or thermal shock would likely damage the relatively brittle ceramics.

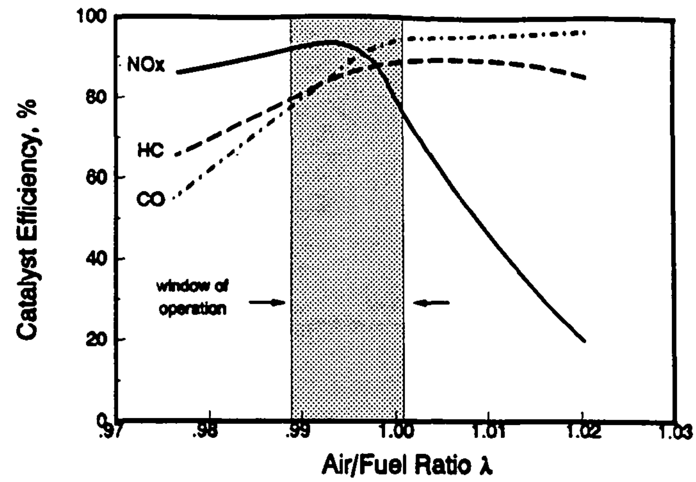


Figure 1: Effect of air-fuel ratio on three-way catalyst efficiency.

The chemical reactions promoted by the catalytic converter take place at the catalyst surface. Because of the cost, a typical catalytic converter contains only a fraction of a gram of the catalytic metals. In order to make efficient use of this expensive material, it is necessary to give it a very high surface area, and to ensure good access by the exhaust gases to the catalyst surface. The most common and damaging maintenance problems with catalytic converters are those which reduce the surface area of catalyst exposed. For example, engine oil will form deposits in the catalytic converter, blocking the pores and destroying its efficiency. Excessive temperatures can cause the metal crystals to sinter together, losing surface area, or even partially melt the ceramic. This causes a loss of porosity and a drop in conversion efficiency. Such high temperatures are most commonly due to excessive combustible materials and oxygen in the exhaust (due to a misfiring cylinder, for instance, or air injection with a very rich mixture). These materials will react in the catalytic converter, and can easily raise its temperature enough to cause permanent damage. Correcting the cause of the misfire will not restore emissions performance unless the catalyst is replaced.

APPENDIX B:

EXPLODED VIEW AND PARTS OF NON-HANDHELD AND HANDHELD ENGINES

This appendix presents exploded views and part lists of engines from Briggs and Stratton, Tecumseh, Kohler, Ryobi, and other manufacturers. Figure 2 shows and Briggs and Stratton side valve engine and Figure 3 shows a discontinued Briggs & Stratton Vanguard 5hp OHV engine.

1. Nut
2. Starter cup
3. Screen
4. Flywheel
5. Baffle
6. Gasket
7. Intake manifold tube
8. Gasket
9. Seal
10. Governor lever
11. Push nut
12. Washer
13. Cylinder block
14. Gasket
15. Breather & tappet cover
16. Head gasket
17. Cylinder head
18. Shroud
19. Governor shaft
20. Key
21. Crankshaft
22. Camshaft
22A. Camshaft, auxiliary pto gear
23. Tappets
24. Key
25. Connecting rod
26. Piston
27. Piston rings
28. Valve retainers
29. Valve springs
30. Intake valve
31. Exhaust valve
32. Piston pin
33. Clips
34. Governor & oil slinger
35. Gasket
36. Crankcase
37. Seal
38. Washer
39. Shaft stop
40. Roll pin
41. Auxiliary pto shaft
42. Seal

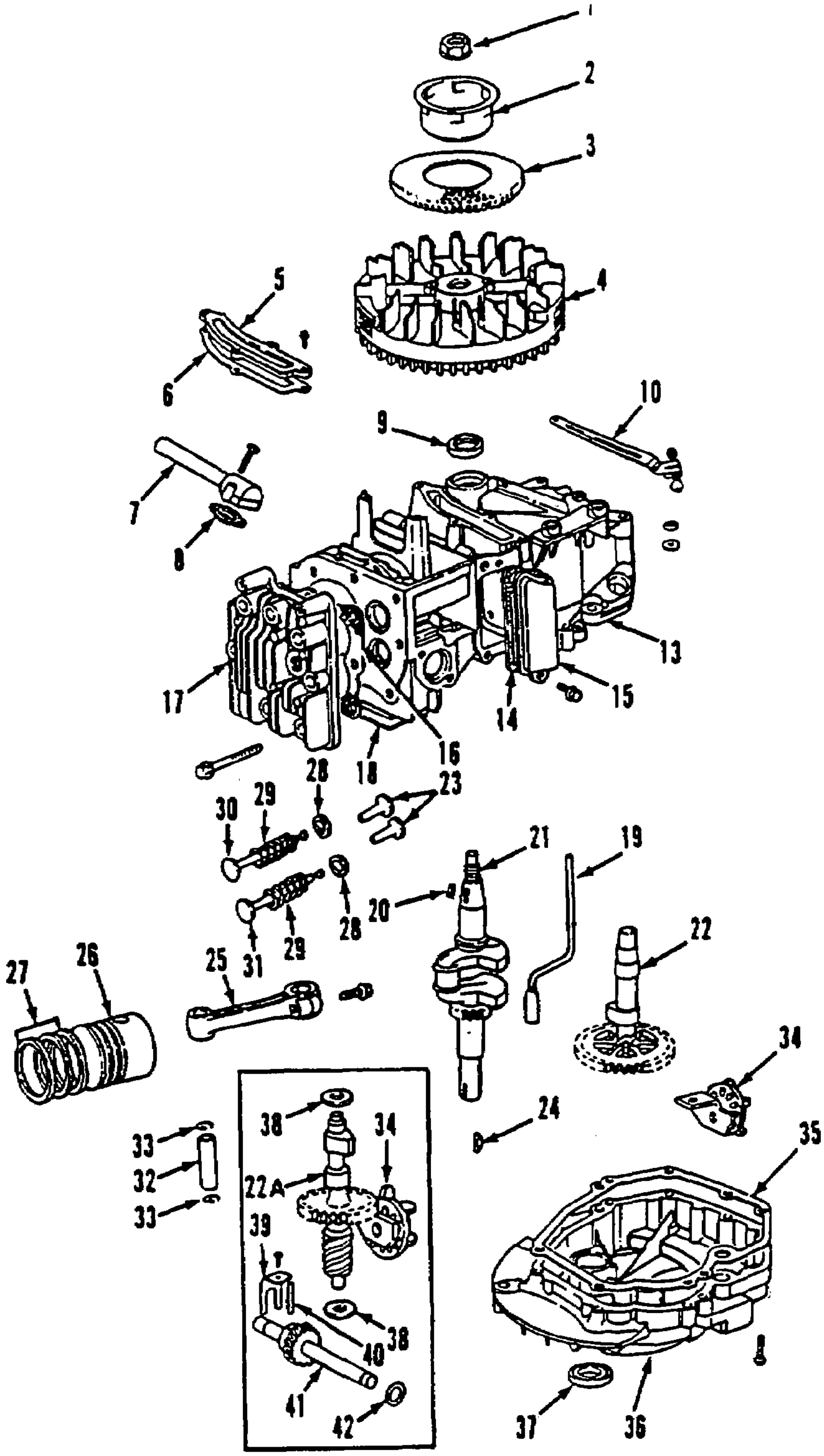
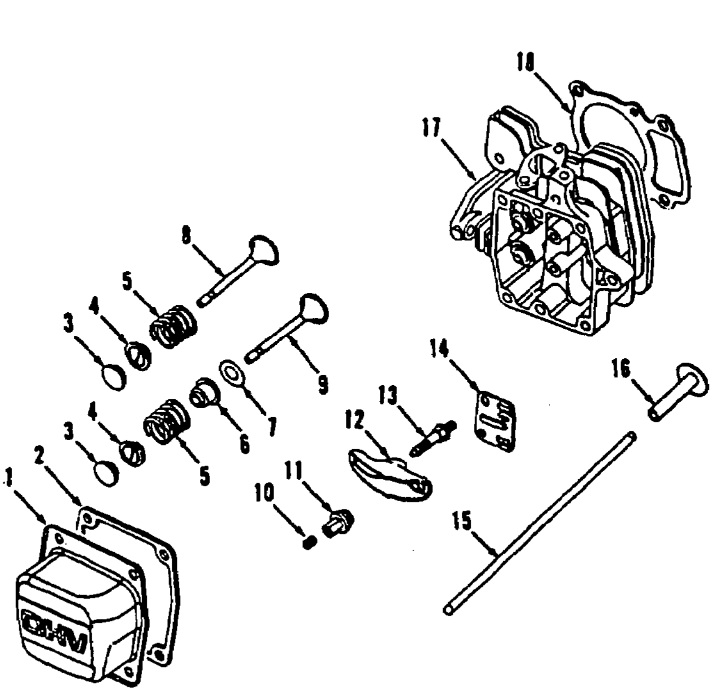


Figure 2: Exploded view of a Briggs & Stratton Series 12 side-valve engine.



1. Rocker cover
2. Gasket
3. Valve cap
4. Valve retainer
5. Valve spring
6. Valve seal
7. Gasket
8. Exhaust valve
9. Intake valve
10. Lock screw
11. Adjusting nut
12. Rocker arm
13. Stud
14. Push rod guide
15. Push rod
16. Valve lifter (tappet)
17. Cylinder head
18. Head gasket

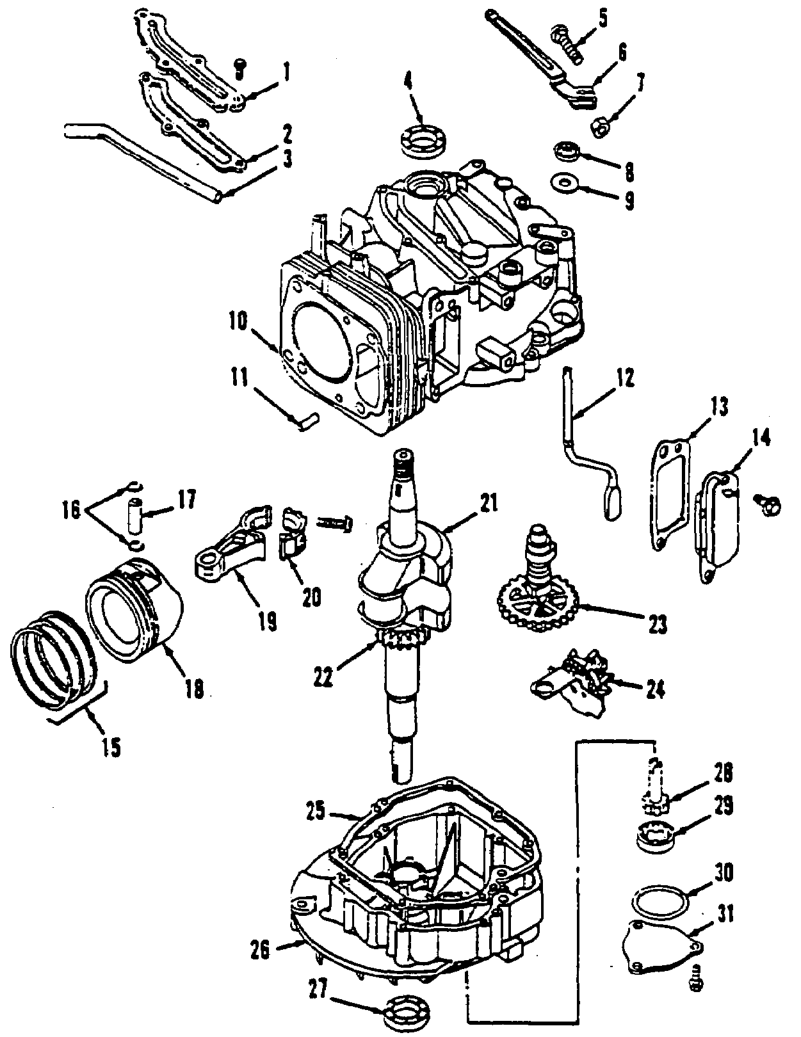


Fig. B514—Exploded view of engine.

1. Cover
2. Gasket
3. Breather tube
4. Oil seal
5. Clamp bolt
6. Governor lever
7. Nut
8. Push nut
9. Washer
10. Crankcase
11. Dowel pin
12. Governor shaft
13. Gasket
14. Tappet cover
15. Piston rings
16. Retaining rings
17. Piston pin
18. Piston
19. Connecting rod
20. Rod cap
21. Crankshaft
22. Gear
23. Camshaft
24. Governor
25. Gasket
26. Oil pan
27. Oil seal
28. Oil pump inner rotc
29. Outer rot
30. "O" ring
31. Cover

Source: (Intertec, 1995a)

Figure 3: Exploded view of a Briggs & Stratton Series 9 overhead-valve engine.

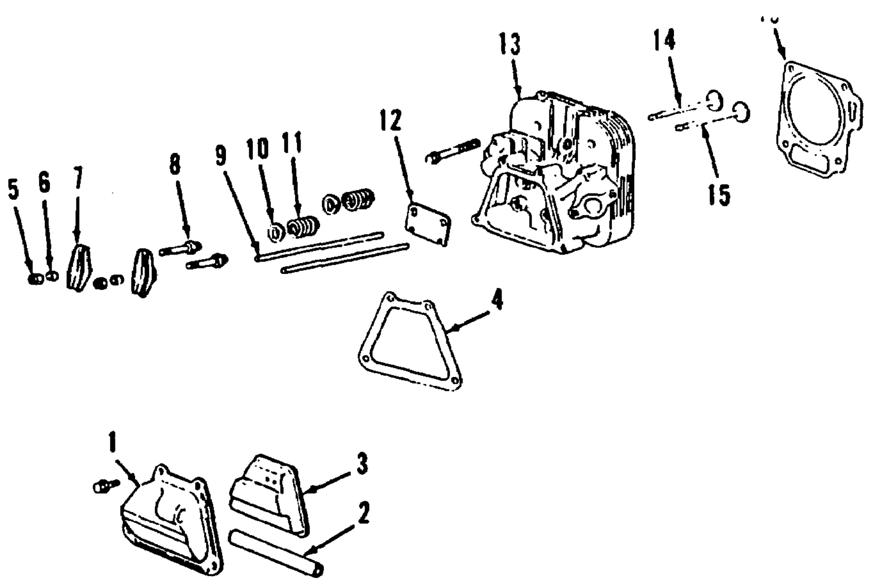


Fig. KO44—Exploded view of cylinder head and valve system.

1. Rocker arm cover
2. Breather hose
3. Breather assy.
4. Gasket
5. Locknut
6. Pivot ball
7. Rocker arm
8. Stud
9. Push rod
10. Valve spring retainer
11. Valve spring
12. Push rod guide plate
13. Cylinder head
14. Exhaust valve
15. Intake valve
16. Gasket

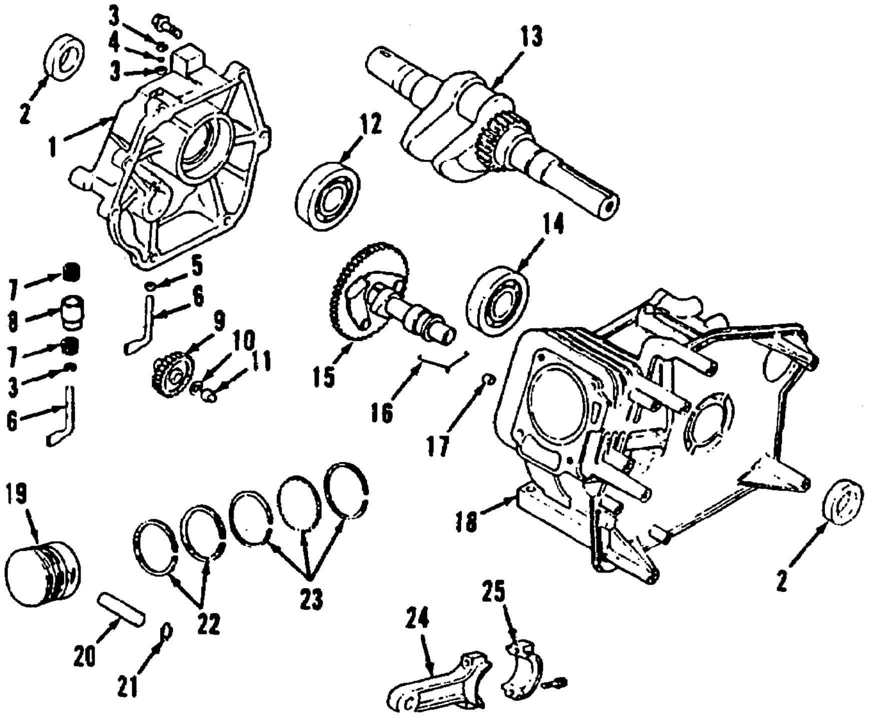


Fig. KO53—Exploded view of engine. Governor components (7 and 8) are used on some engines.

1. Crankcase cover
2. Crankshaft seals
3. Washer
4. Snap ring
5. Washer
6. Governor shaft
7. Needle bearings
8. Bushing
9. Governor gear
10. Spacer
11. Stub shaft
12. Main bearing
13. Crankshaft
14. Main bearing
15. Camshaft assy.
16. Compression release spring
17. Dowel
18. Crankcase
19. Piston
20. Piston pin
21. Snap ring
22. Compression rings
23. Oil ring
24. Connecting rod
25. Rod cap

Source: (Intertec, 1995a)

Figure 4: Exploded view of a Kohler C5 overhead-valve engine.

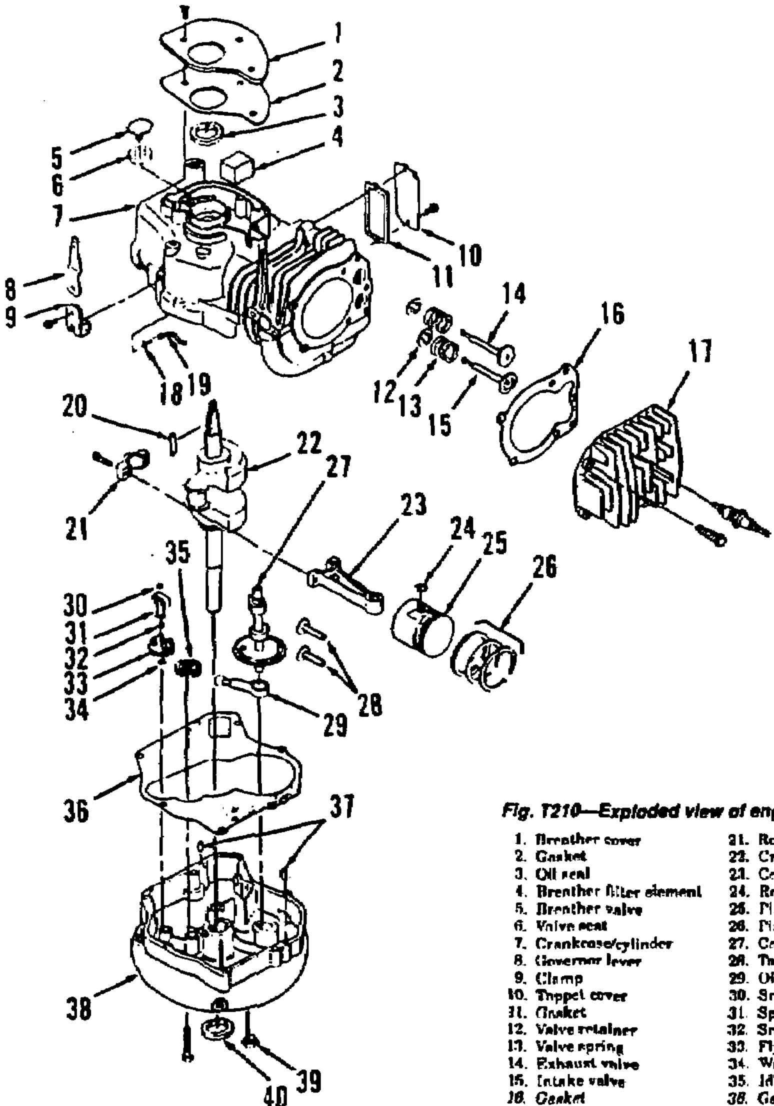
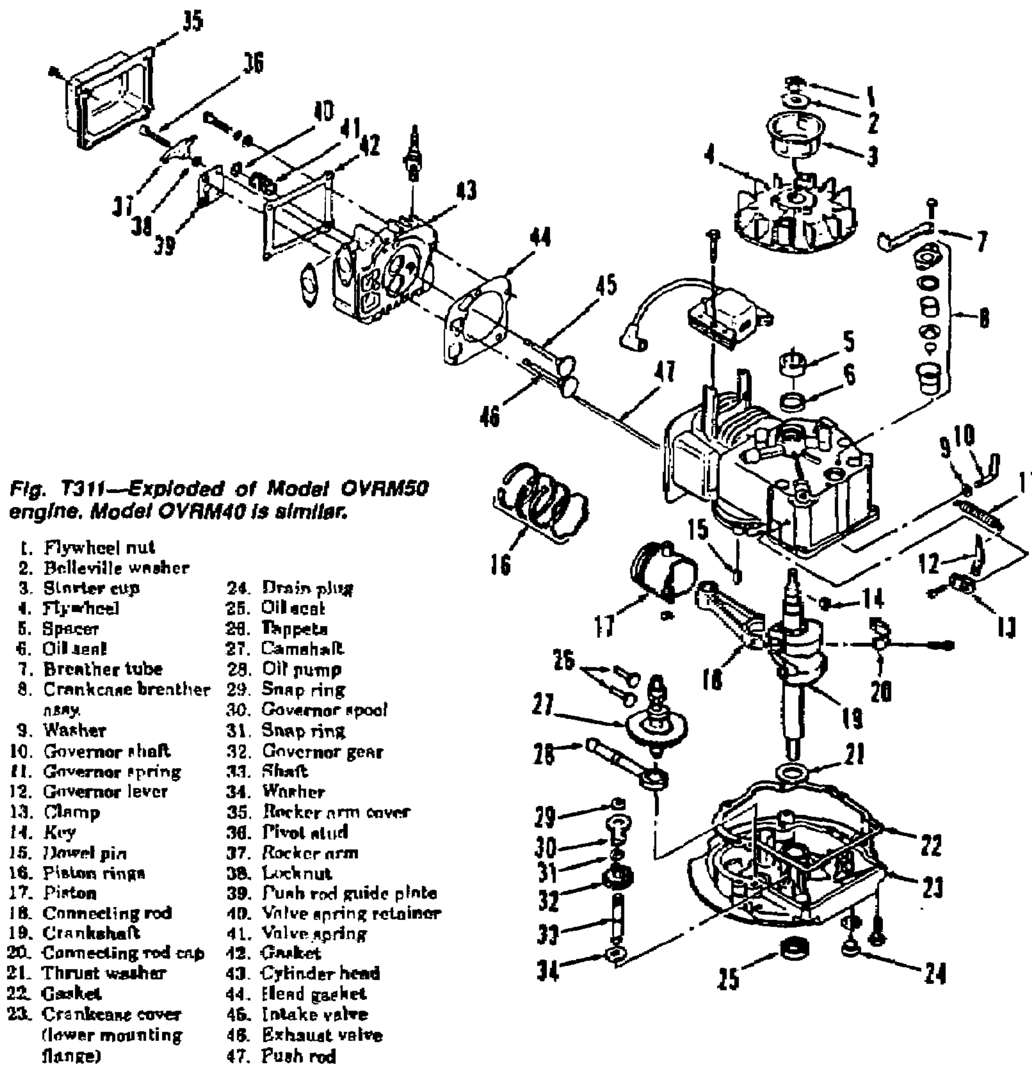


Fig. T210—Exploded view of engine.

1. Breather cover
2. Gasket
3. Oil seal
4. Breather filter element
5. Breather valve
6. Valve seat
7. Crankcase/cylinder
8. Governor lever
9. Clamp
10. Tappet cover
11. Gasket
12. Valve retainer
13. Valve spring
14. Exhaust valve
15. Intake valve
16. Gasket
17. Cylinder head
18. Washer
19. Governor shaft
20. Key
21. Rod cap
22. Crankshaft
23. Connecting rod
24. Retaining ring
25. Piston & pin
26. Piston rings
27. Camshaft
28. Tappets
29. Oil pump
30. Snap ring
31. Spool
32. Snap ring
33. Flyweight & gear
34. Washer
35. Idler gear
36. Gasket
37. Dowel pins
38. Oil pan
39. Drain plug
40. Oil seal

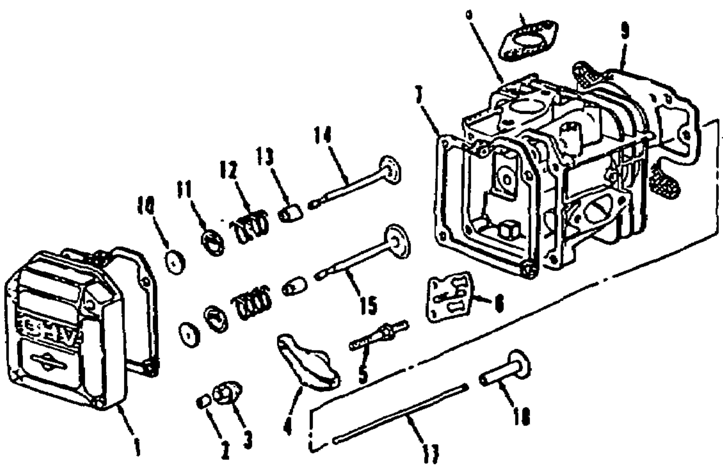
Source: (Intertec, 1995a)

Figure 5: Exploded view of a Tecumseh VLV55 side-valve engine.



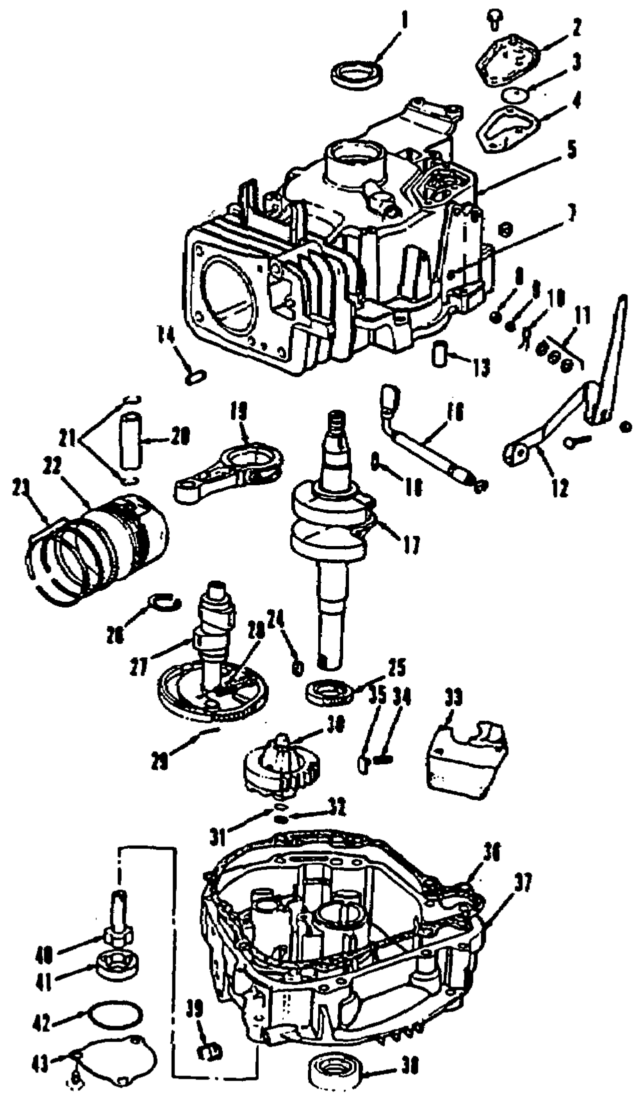
Source: (Intertec, 1995a)

Figure 6: Exploded view of a Tecumseh OVRM55 overhead-valve engine.



1. Rocker cover
2. Lock screw
3. Adjusting nut
4. Rocker arm
5. Stud
6. Push rod guide
7. Gasket
8. Cylinder head
9. Head gasket
10. Valve cap
11. Valve retainer
12. Valve spring
13. Valve seal
14. Exhaust valve
15. Intake valve
16. Exhaust gasket
17. Push rod
18. Cam follower (tappet)

1. Oil seal
2. Breather cover
3. Breather valve
4. Gasket
5. Crankcase
7. Governor shaft bushing
8. Seal
9. Washer
10. Cotter pin
11. Washers
12. Governor lever
13. Dowel pin
14. Dowel pin
16. Governor shaft
17. Crankshaft
18. Key
19. Connecting rod
20. Piston pin
21. Clips
22. Piston
23. Piston rings
24. Key
25. Gear
26. Snap ring
27. Camshaft
28. Compression release spring
29. Oil pump drive pin
30. Governor gear & flyweight
31. Snap ring
32. Washer
33. Oil screen
34. Spring
35. Oil pressure relief valve
36. Gasket
37. Oil pan
38. Oil seal
39. Drain plug
40. Oil pump inner rotor
41. Outer rotor
42. "O" ring
43. Oil pump cover



Source: (Intertec, 1995a)

Figure 7: Exploded view of a Briggs & Stratton Vanguard overhead-valve engine.

Illustrated Parts List
Industrial/Commercial®
Model Series
12G700 to 12G799

TYPE NUMBER
2615

TO FIND
THE CORRECT NUMBER OF THE PART YOU NEED: FOLLOW THE INSTRUCTIONS BELOW

A. *Refer to Engine Model, Type and Code Number that is stamped on the blower housing of engine.* Engine type numbers such as 0123 01 are listed only as 0123 in most instances. The two digits (01 *or 02, etc.) to the right of the space may be required for more accurate parts identification in some* instances. Select the Illustrated Parts List covering the correct Model Series and Type Number.

B. Refer to the Illustrations and compare the original part with Illustration. The number next to the *Illustration is the Reference Number. Assemblies include all parts shown in frames. All parts shown* in assembly frames having individual reference numbers can be purchased separately.

C. After the Reference Number has been identified, refer to the Numerical text, where Reference and Primary Part Number are listed. THE PRIMARY PART IS USED ON ALL TYPE NUMBERS EXCEPT THOSE TYPE NUMBERS UNDER "NOTE."

D. If a "Note" appears below the Primary Part Number, it means that this part differs from the Primary Part for certain types. If your Type number is listed under "Note," order the part referred to at the "Note."

E. If your Engine Type Number does not appear after any part number listed under "Note," use the Primary Part Number.

F. For Engine Type Numbers not covered by this book, check other Parts Lists having the same engine model or contact your source of supply.

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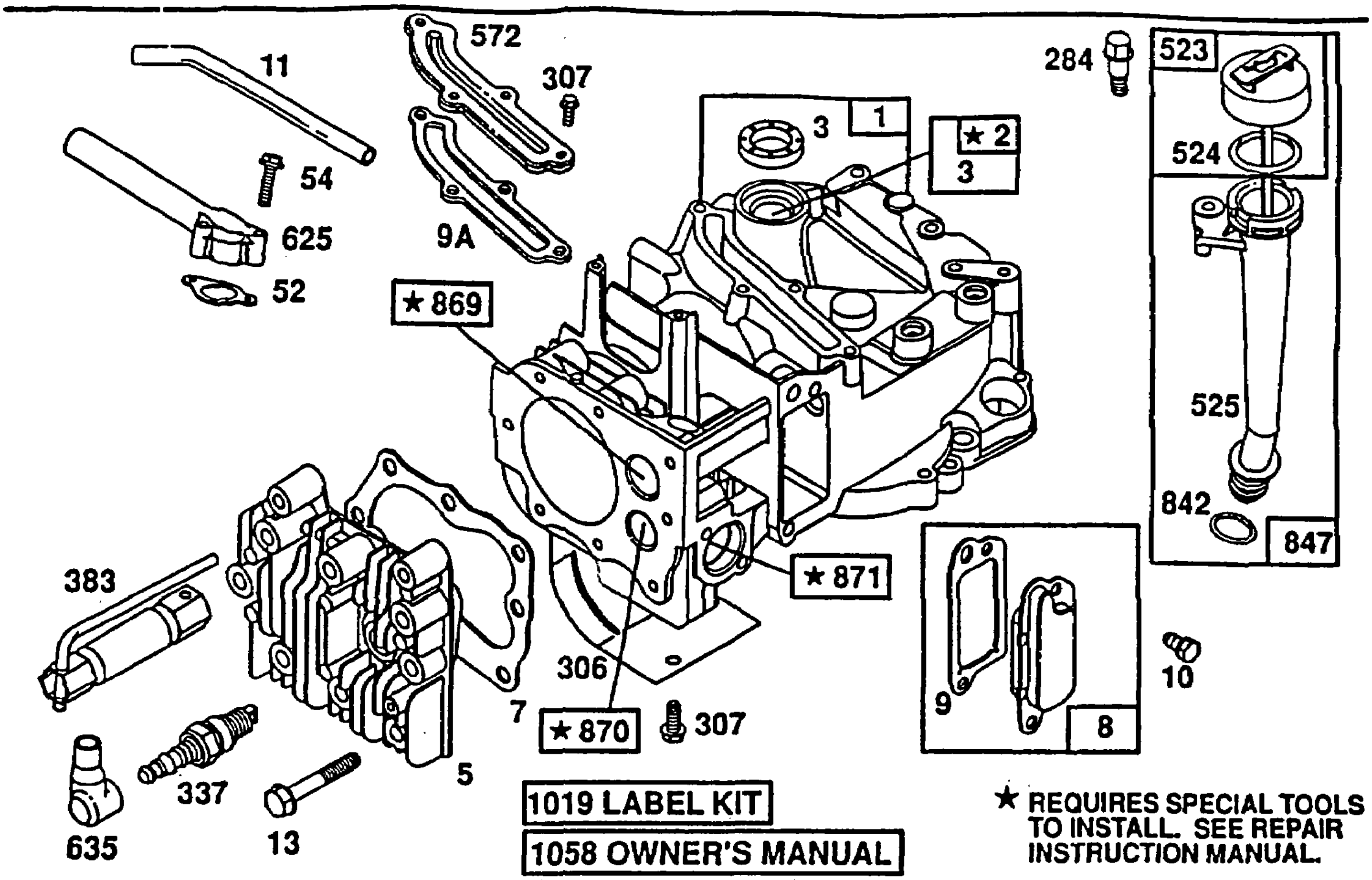
BRIGGS & STRATTON®

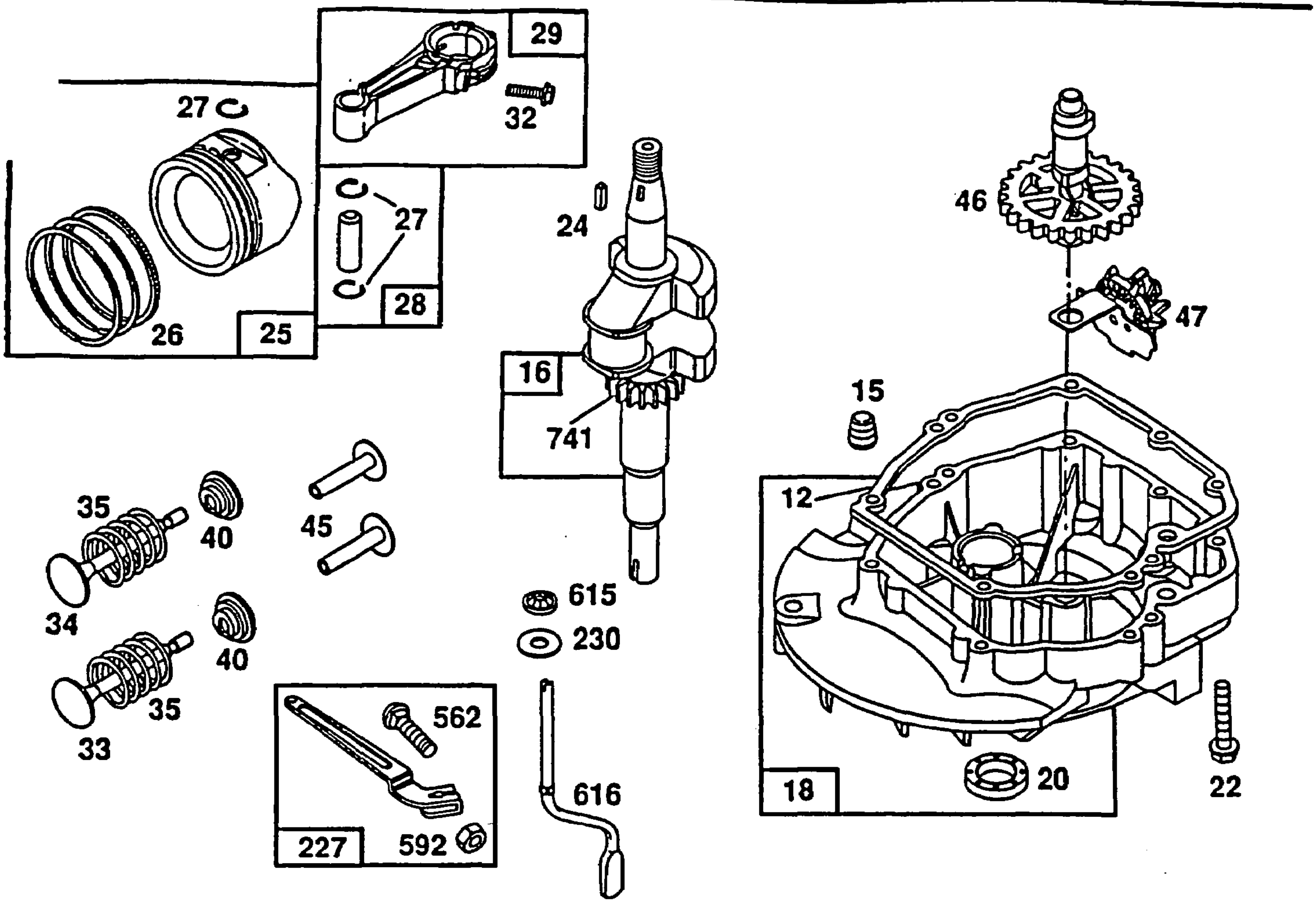
12G700 to 12G799



REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION
1	494062	Cylinder Assembly	54	94526	Screw-Hex. Head	625	281085	Manifold-Intake
2	399269	Bushing	284	94511	Screw-Hex. Head	635	66538	Elbow-Spark Plug
3	★299819	Seal-Oil	306	224324	Shield-Cylinder	842	★280966	Seal-O-Ring
5	214349	Head-Cylinder	307	94515	Screw-Hex. Head	847	495263	Tube-Oil Fill
7	★272916	Gasket-Cylinder Hd.	337	802592	Plug-Spark	869	213512	Seat-Intake Valve
8	495786	Breather Assembly			(Resistor Type)	870	213513	Seat-Exhaust Valve
9	★272481	Gasket-Valve Cover			(1-7/8" High, 48 mm)	871	262001	Guide-Exhaust Valve
9A	★272238	Gasket-Baffle Plate	383	89838	Wrench-Spark Plug			——— Note ———
10	94650	Screw-Hex. Head	523	495264	Cap-Oil Fill			63709 Guide-Intake
11	231933	Tube-Breather	524	★280393	Seal-Filler Tube			Valve
13	94547	Screw-Cylinder Hd.	525	495265	Tube-Oil Fill	1019	494256	Label Kit
52	★272199	Gasket-Intake Elbow	572	224328	Baffle-Cylinder	1058	272262	Owner's Manual

Included in Gasket Set-Part No 497316.
Included in Carburetor Kit-Part No. 493762.
◆ Included in Carburetor Gasket Set-Part No. 490937.

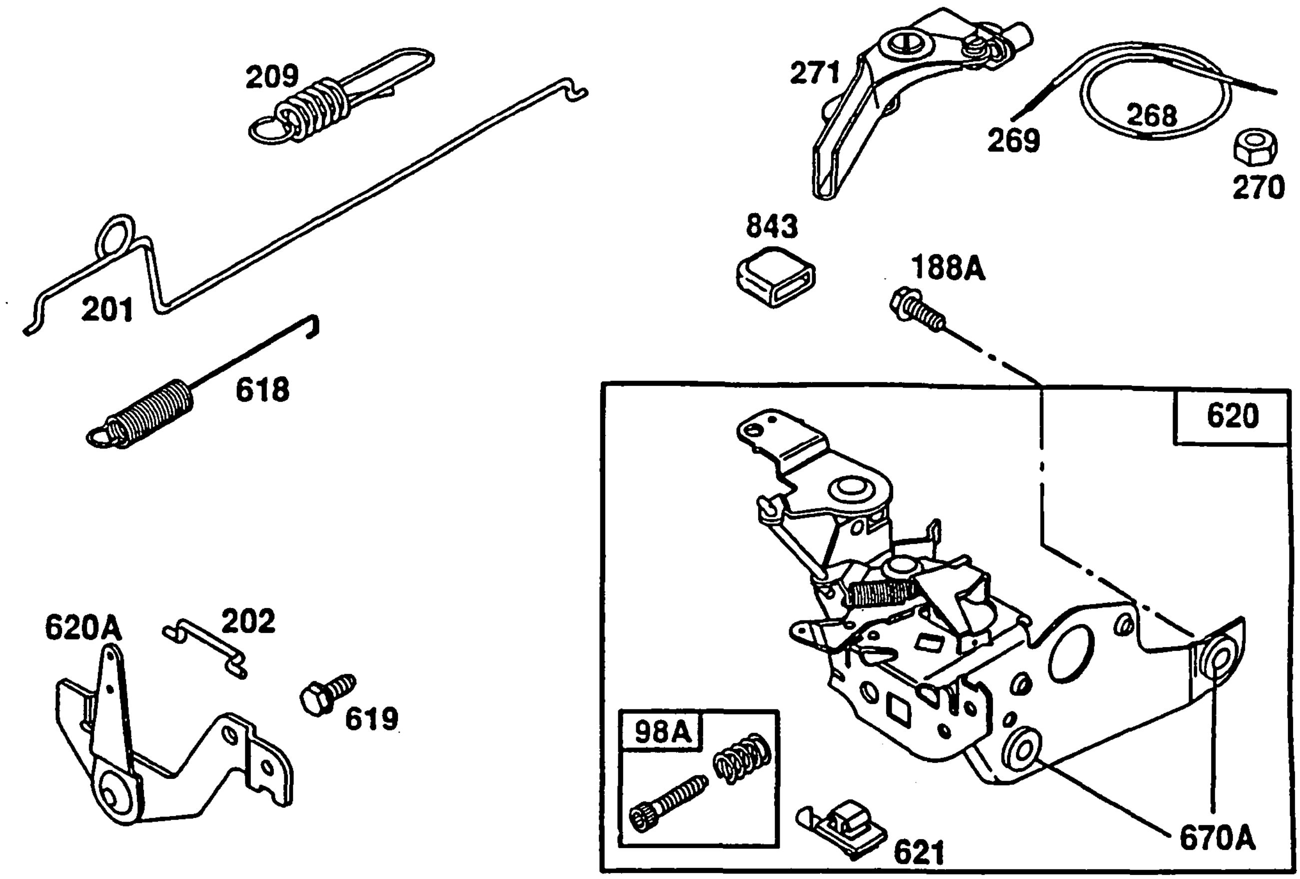
Assemblies include all parts shown in frames.



REF. NO.	PART NO.	DESCRIPTION
12	★272198	Gasket–Crankcase
15	94720	Plug–Oil Drain
16	493362	Crankshaft
		——— Note ——— For Timing Gear Key– Order Part No. 94388.
18	493279	Sump–Engine
20	★399781	Seal–Oil
22	94220	Screw–Hex. Head
		——— Note ——— 94612 Screw–Hex. Head One Used in Hole Nearest Breather.
24	222698	Key–Flywheel
25	494058	Piston Assy. (Standard)
	494059	Piston Assy. (.010" O.S.)
	494060	Piston Assy. (.020" O.S.)
	494061	Piston Assy. (.030" O.S.)
26	493261	Ring Set (Standard)
	493388	Ring Set (.010" O.S.)
	493389	Ring Set (.020" O.S.)
	493390	Ring Set (.030" O.S.)
27	26026	Lock–Piston Pin
28	298909	Pin–Piston (Standard)
	298908	Pin–Piston (.005" O.S.)
29	490566	Rod–Connecting
	490743	Rod–Connecting (.020" Undersize)
32	94699	Screw–Connecting Rod
33	262651	Valve–Exhaust
34	262652	Valve–Intake
35	262224	Spring–Valve
40	93312	Retainer–Valve
45	262204	Tappet–Valve
46	492830	Gear–Cam
47	493737	Slinger–Oil
227	492349	Lever–Governor
230	67072	Washer–Governor Crank
562	92613	Bolt–Governor Lever
592	231082	Nut–Hex.
615	94474	Fastener
616	262578	Crank–Governor
741	262598	Gear–Timing

★ Included in Gasket Set–Part No 497316.
● Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

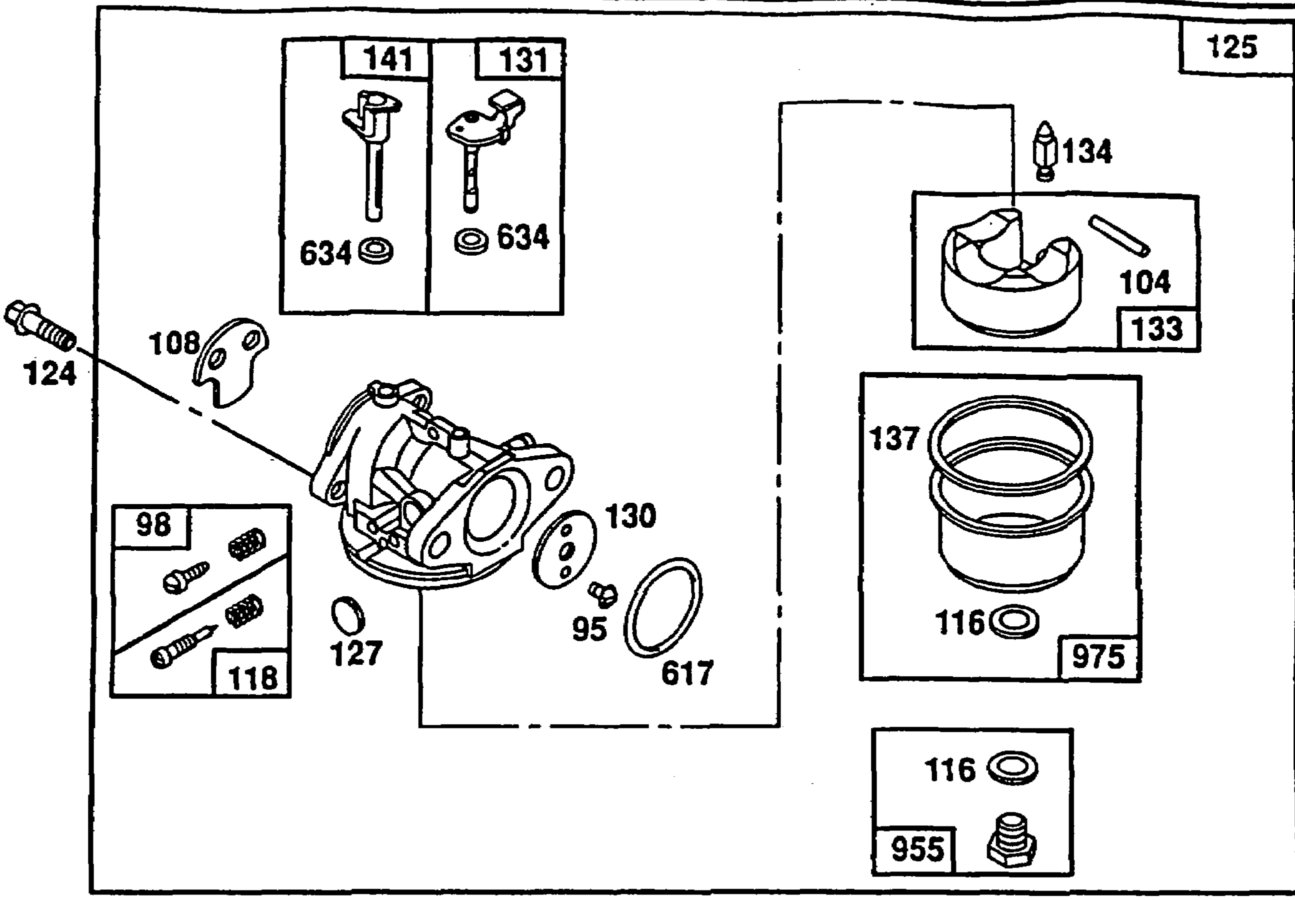
Assemblies include all parts shown in frames.



REF. NO.	PART NO.	DESCRIPTION
98A	493280	Screw–Speed Adj.
188A	94644	Screw–Hex. Head
201	262579	Link–Governor
202	262782	Link–Control
209	262660	Spring–Governor
268	66986	Casing–Wire (48" Long) ——— Note ——— If Longer Casing is Needed, Specify Length in Inches and Cut to Required Length.
269	26099	Wire–Control (54" Long) ——— Note ——— If Longer Wire is Needed, Specify Length in Inches and Cut to Required Length.
270	63426	Locknut–Casing
271	290568	Lever–Control
618	262749	Spring–Return
619	94620	Screw–Self Tap
620	495976	Bracket–Control
620A	494112	Bracket–Control
621	396847	Switch–Stop
670A	493823	Spacer–Bracket (Includes 2)
843	272616	Sleeve–Control

★ Included in Gasket Set–Part No 497316.
● Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.



F.).	PART NO.	DESCRIPTION
95	94098	Screw–Round Head
98	398185	Screw–Idle Adjustment
104	•231371	Pin–Float Hinge
108	223471	Valve–Choke
116•◆		Gasket–Sealing (Sold in Kit Only).
118	493765	Valve–Needle
124	94525	Screw–Carburetor Mounting
125	494217	Carburetor

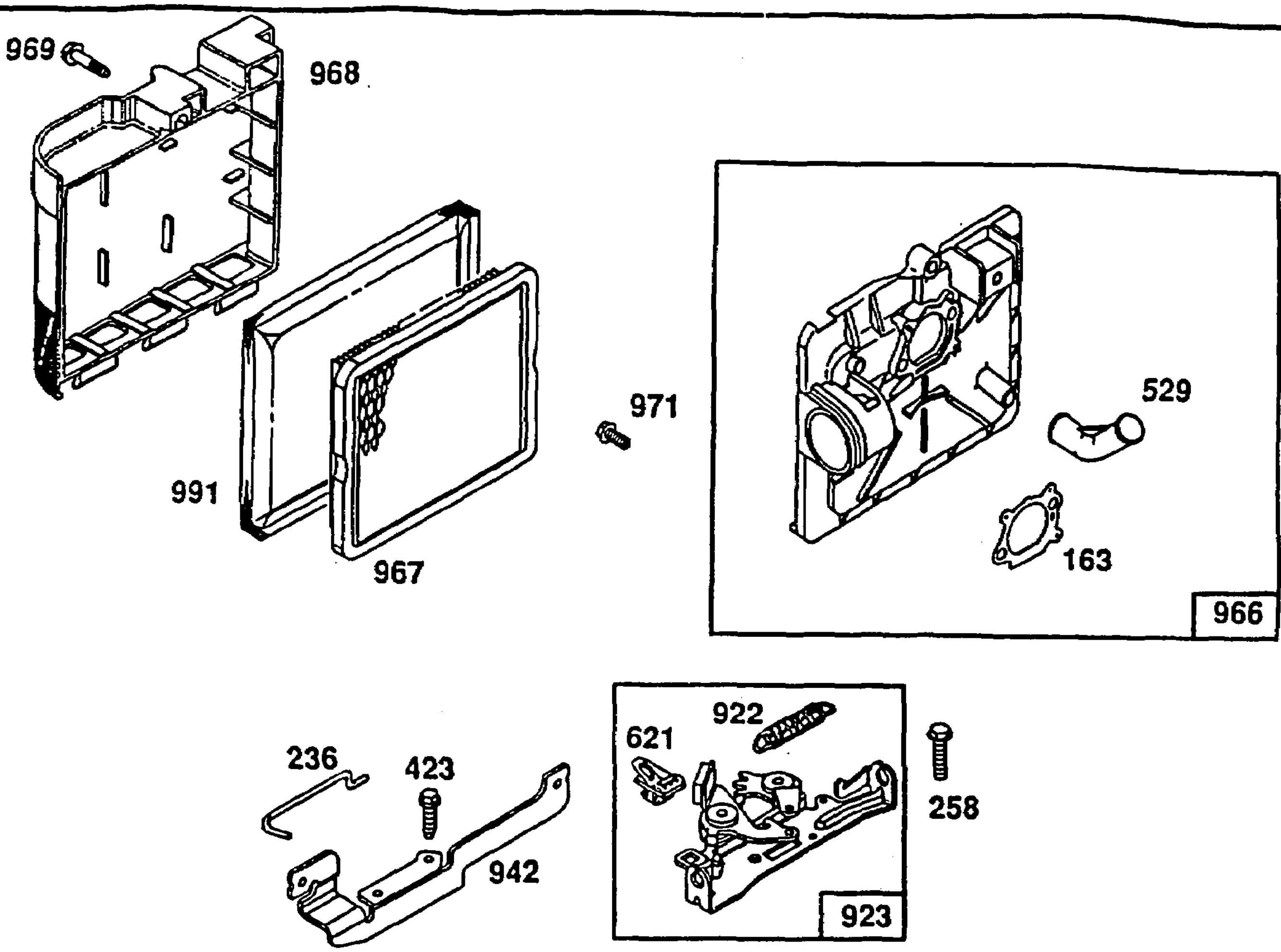
REF. NO.	PART NO.	DESCRIPTION
127 •		Plug–Welch (Sold in Kit Only).
130	223470	Valve–Throttle
131	493267	Shaft–Throttle
133	398187	Float–Carburetor
134	•398188	Valve–Needle (Includes Seat)
137•◆		Gasket–Bowl (Sold in Kit Only).
141	494218	Shaft–Choke

REF. NO.	PART NO.	DESCRIPTION
617	•◆270344	Seal–Intake Elbow
634•◆		Washer–Shaft (Sold in Kit Only).
955	493869	Screw–Bowl Mtg. (Standard) ——— Note ——— 493763 Screw–Bowl Mtg. (High Altitude)
975	493640	Bowl–Float

uded in Gasket Set–Part No 497316.
• Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.

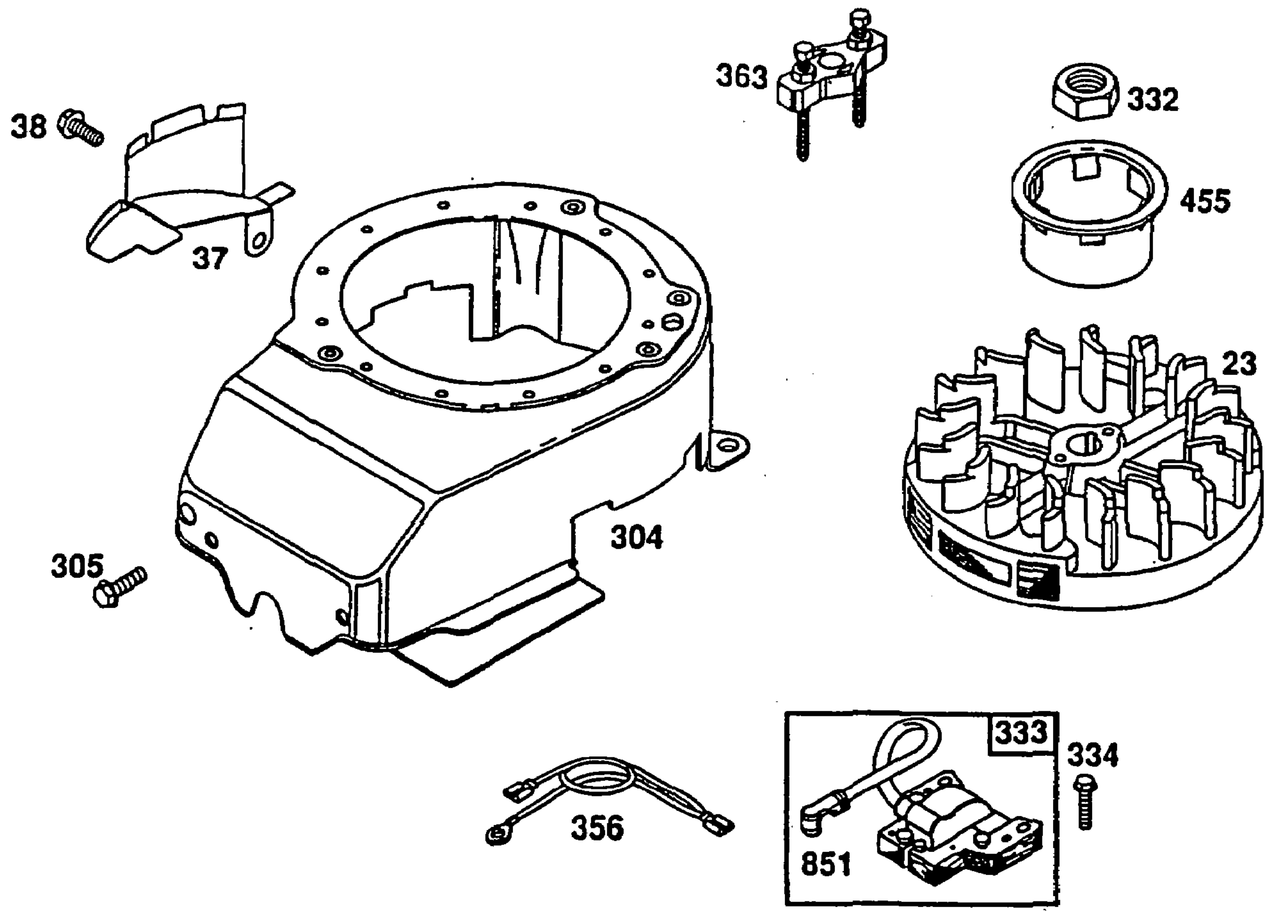
12G700 to 12G799



REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION
163	★272653	Gasket-Air Cleaner	621	396847	Switch-Stop	967	491588	Filter-Air
236	262461	Link-Lock Out	922	262640	Spring-Brake	968	281340	Cover-Air Cleaner
258	94512	Screw-Hex. Head	923	493442	Brake Assembly	969	94120	Screw-Cover Mtg.
423	93758	Screw-Hex. Head	942	224494	Bracket-Brake	971	94121	Screw-Air Cleaner
529	281299	Grommet	966	496116	Base-Air Cleaner	991	493537	Pre-Filter

★ Included in Gasket Set-Part No 497316.
● Included in Carburetor Kit-Part No. 493762.
◆ Included in Carburetor Gasket Set-Part No. 490937.

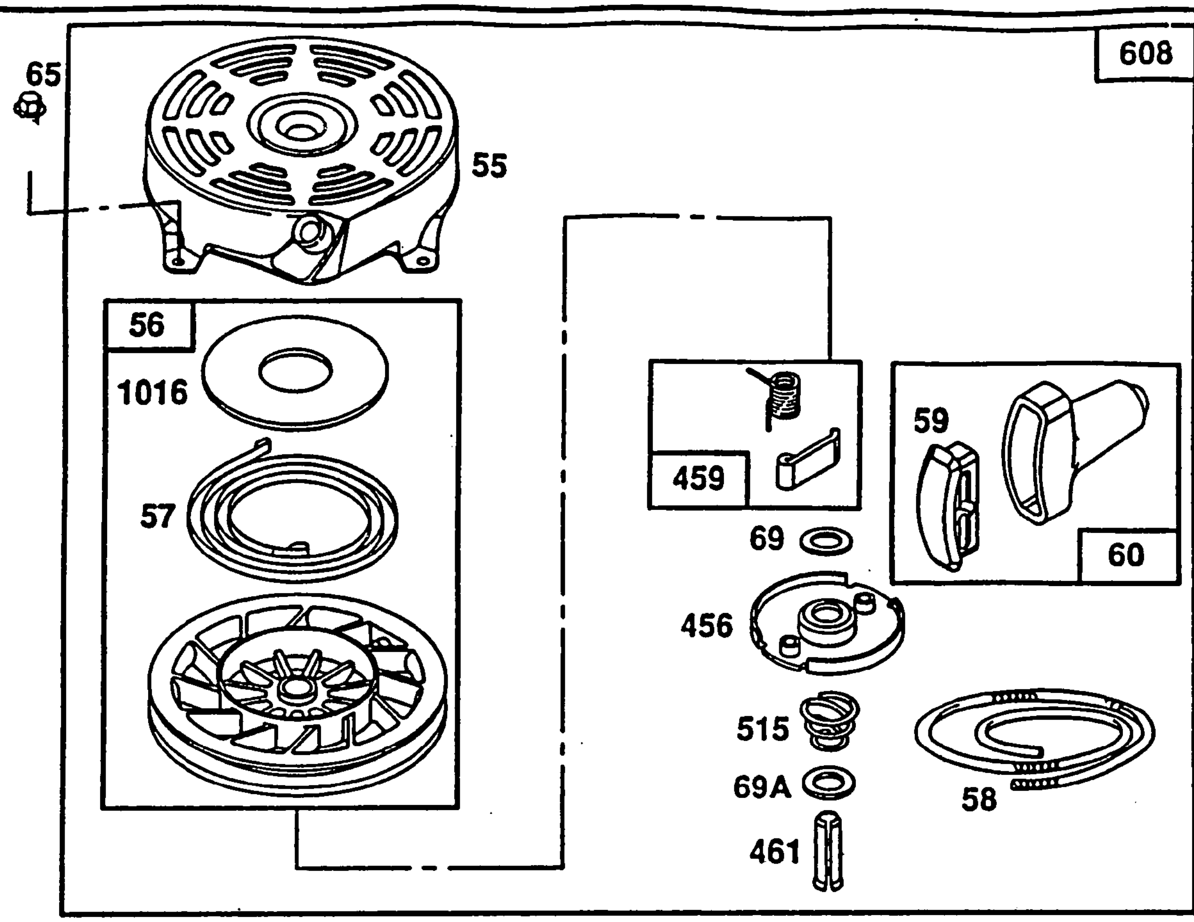
Assemblies include all parts shown in frames.



REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION
23	492177	Flywheel	305	94729	Screw-Sem	356	398708	Wire-Stop
37	224511	Guard-Flywheel	332	92284	Nut-Flywheel	363	19069	Puller-Flywheel
38	94619	Screw-Hex. Head	333	802574	Armature-Magneto	455	224250	Cup-Starter
304	493293	Housing-Blower	334	94731	Screw-Sem	851	493880	Terminal-Cable

★ Included in Gasket Set-Part No 497316.
● Included in Carburetor Kit-Part No. 493762.
◆ Included in Carburetor Gasket Set-Part No. 490937.

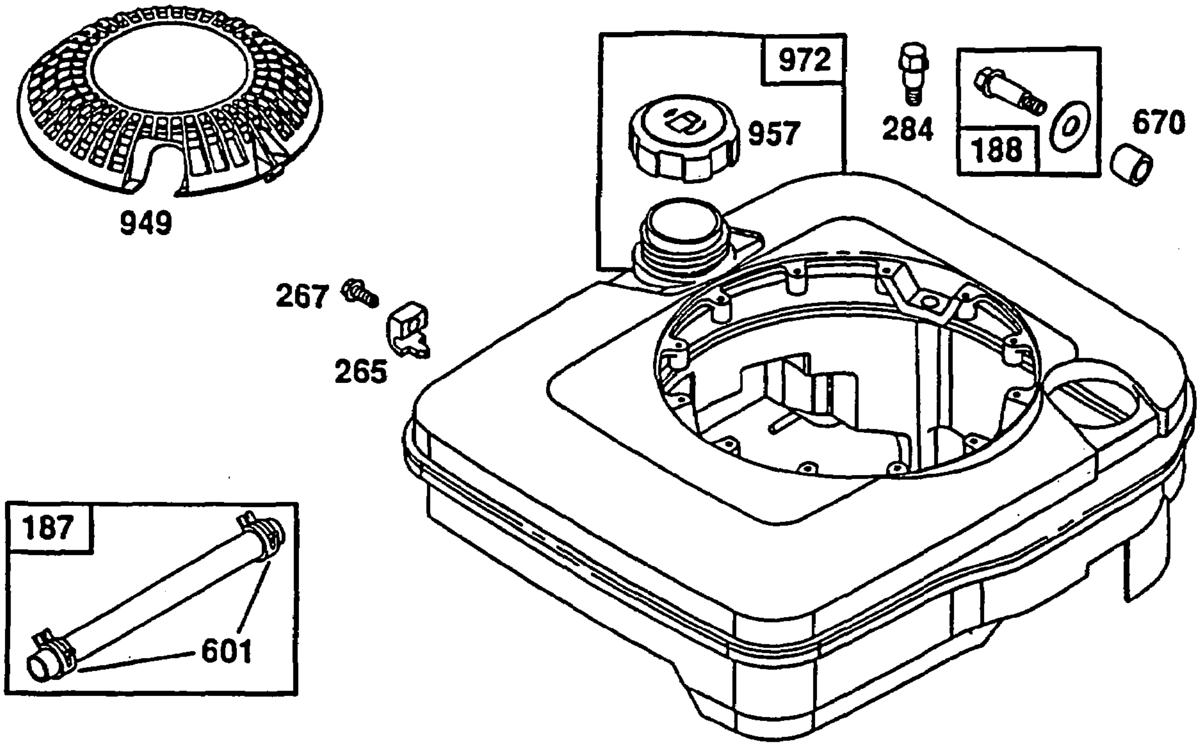
Assemblies include all parts shown in frames.



REF. NO.	PART NO.	DESCRIPTION
55	492831	Housing–Rewind Starter
56	493824	Pulley–Starter
57	262594	Spring–Rewind Starter
58	280399	Rope–Starter (Cut To 88-5/8")
59	396892	Insert–Handle
60	393152	Grip–Starter Rope
65	94579	Screw–Hex. Head
69	280973	Washer–Spring
69A	224322	Washer–Flat
456	224321	Retainer–Spring
459	492833	Pawl–Ratchet
461	262626	Pin–Shaft
515	262625	Spring–Retainer
608	493295	Starter–Rewind Include(s): 94128 Screw–Hex. Head 92987 Nut–Hex.
1016	224278	Cover–Pulley

.. Included in Gasket Set–Part No 497316.
● Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.

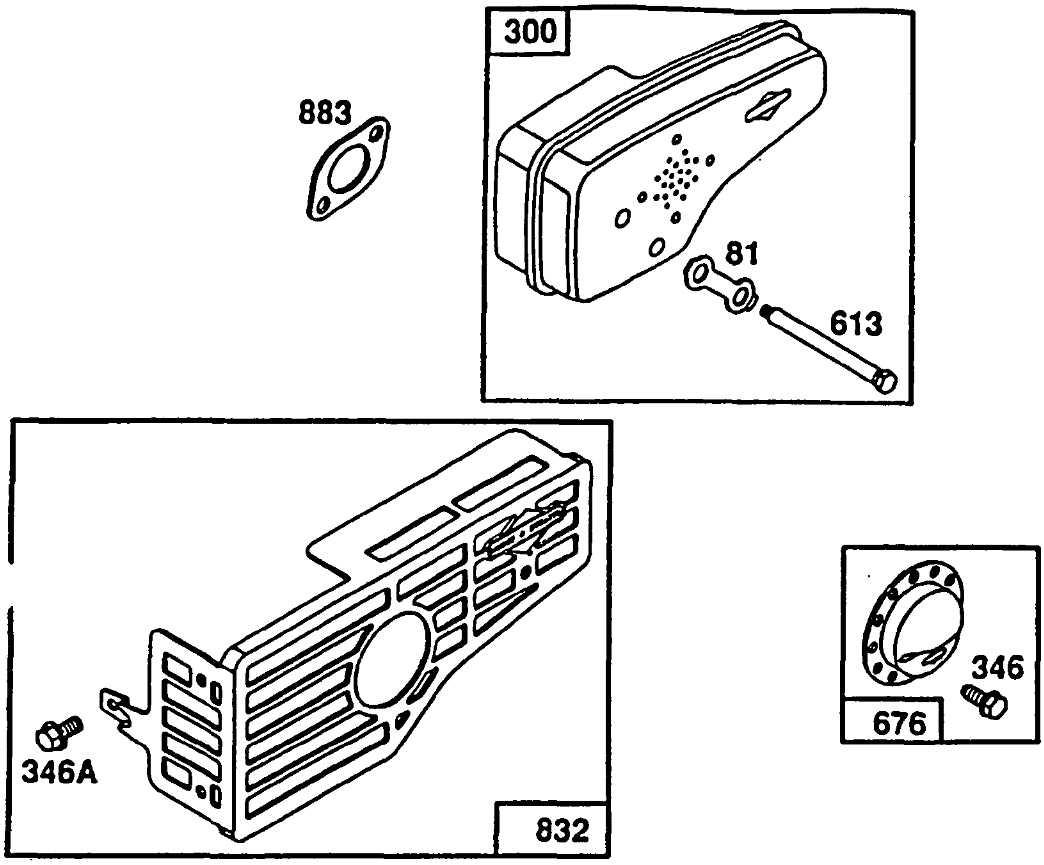


REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION
187	492790	Line–Fuel (6-3/4" Long)	267	94694	Screw–Self Tap	949	281136	Guard–Finger
188	398540	Screw–Tank Mounting	284	94511	Screw–Hex. Head	957	397974	Cap–Fuel Tank
265	213146	Clamp–Casing	601	93053	Clamp–Hose	972	497224	Tank–Fuel
			670	280512	Spacer–Fuel Tank			

★ Included in Gasket Set–Part No 497316.
● Included in Carburetor Kit–Part No: 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.

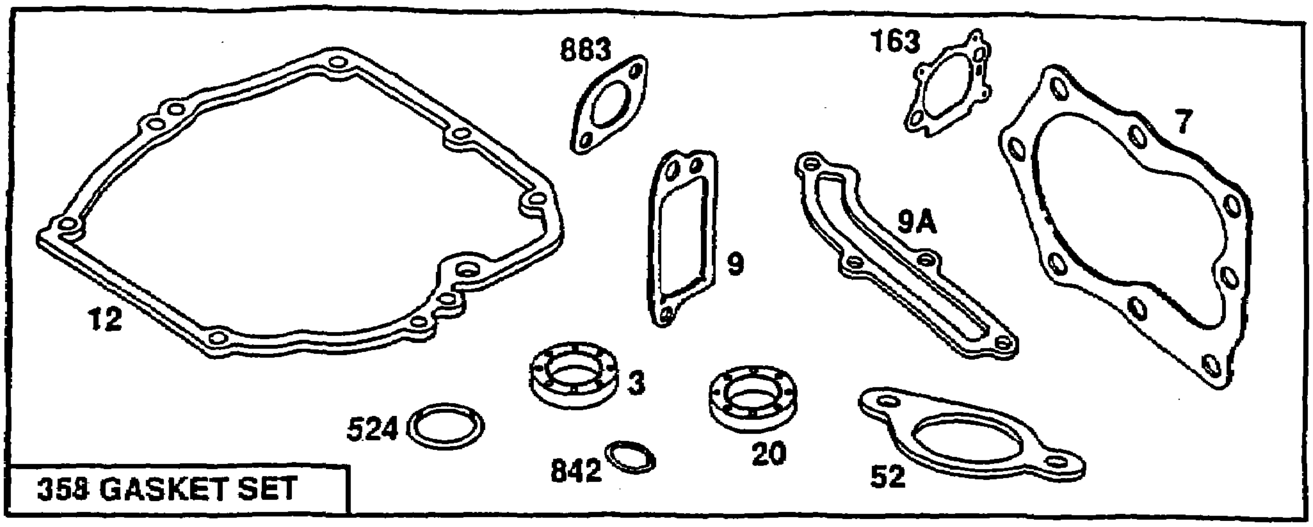
12G700 to 12G799

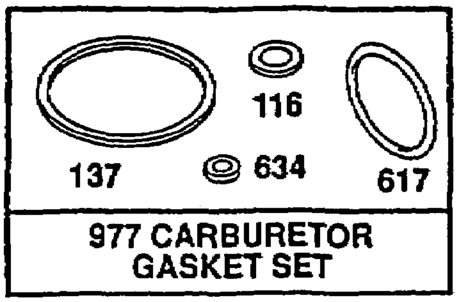


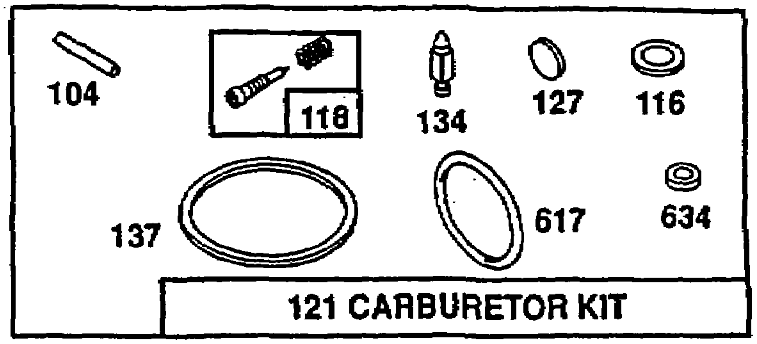
REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION	REF. NO.	PART NO.	DESCRIPTION
81	223664	Lock–Muffler Screw	346A	94602	Screw–Hex. Head	832	494224	Guard–Muffler
300	496106	Muffler–Exhaust	613	94231	Screw–Hex. Head	883	⁎272253	Gasket–Muffler
346	93705	Screw–Hex. Head	676	396548	Deflector–Muffler			

⁎ Included in Gasket Set–Part No 497316.
● Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.







REF. NO.	PART NO.	DESCRIPTION
3	★299819	Seal–Oil
7	★272916	Gasket–Cylinder Hd.
9	★272481	Gasket–Breather
9A	★272238	Gasket–Breather
12	★272198	Gasket–Crankcase
20	★399781	Seal–Oil
52	★272199	Gasket–Intake Elbow
104	•231371	Pin–Float Hinge
'16 •◆		Gasket–Sealing (Sold in Kit Only).
118	•493765	Valve–Needle
121	493762	Carburetor Kit
127 •		Plug–Welch (Sold in Kit Only).
134	•398188	Valve–Needle (Includes Seat)
137 •◆		Gasket–Bowl (Sold in Kit Only).
163	★272653	Gasket–Air Cleaner
358	497316	Gasket Set
524	★280393	Seal–Filler Tube
617 •◆	270344	Seal–Intake Elbow
634 •◆		Washer–Shaft (Sold in Kit Only).
842	★280966	Seal–O–Ring
883	★272253	Gasket–Muffler
977	490937	Gasket Set–Carburetor

★ Included in Gasket Set–Part No 497316.
• Included in Carburetor Kit–Part No. 493762.
◆ Included in Carburetor Gasket Set–Part No. 490937.

Assemblies include all parts shown in frames.

FORM MS-2518-3/95
REPLACES FORM MS-2518-5/94
FILE IN SECT. 2 OF SERVICE MANUAL

Illustrated Parts List

Model Series

99700 to 99799

TYPE NUMBERS
0100 through 0103,
0110 through 0118,
0601, 0606,
0610, 0611, 0612,
0614, 0615,
0618 through 0626,
0630 through 0638,
0814, 0916, 0918,
0920, 0925, 0934,
0935, 0937, 0938,
0942, 0945,

TYPE NUMBERS
3015, 3016,
3024 through 3026,
3101, 3102, 3103,
3111 through 3120,
3141 through 3143,
3515, 3525, 3601,
3608 through 3613,
3616, 3617, 3620,
3624, 3925, 3641,
3642, 3643, 3650.

TO FIND
THE CORRECT NUMBER OF THE PART YOU NEED:
FOLLOW THE INSTRUCTIONS BELOW

A. Refer to the Engine Model, Type and Code Number that is stamped on the blower housing of engine. Engine type numbers such as 0123 01 are listed only as 0123 in most instances. The two digits (01 or 02, etc.) to the right of the space may be required for more accurate parts identification in some instances. Select the Illustrated Parts List covering the correct Model Series and Type Number.

B. Refer to the illustrations and compare the original part with illustration. The number next to the illustration is the Reference Number. Assemblies include all parts shown in frames. All parts shown in assembly frames having individual reference numbers can be purchased separately.

C. After the Reference Number has been identified, refer to the Numerical text, where Reference and Primary Part Number are listed. THE PRIMARY PART IS USED ON ALL TYPE NUMBERS EXCEPT THOSE TYPE NUMBERS UNDER "NOTE."

D. If a "Note" appears below the Primary Part Number, it means that this part differs from the Primary Part for certain types. If your Type number is listed under "Note," order the part referred to at the "Note."

E. If your Engine Type Number does not appear after any part number listed under "Note," use the Primary Part Number.

F. For Engine Type Numbers not covered by this book, check other Parts Lists having the same engine model or contact your source of supply.

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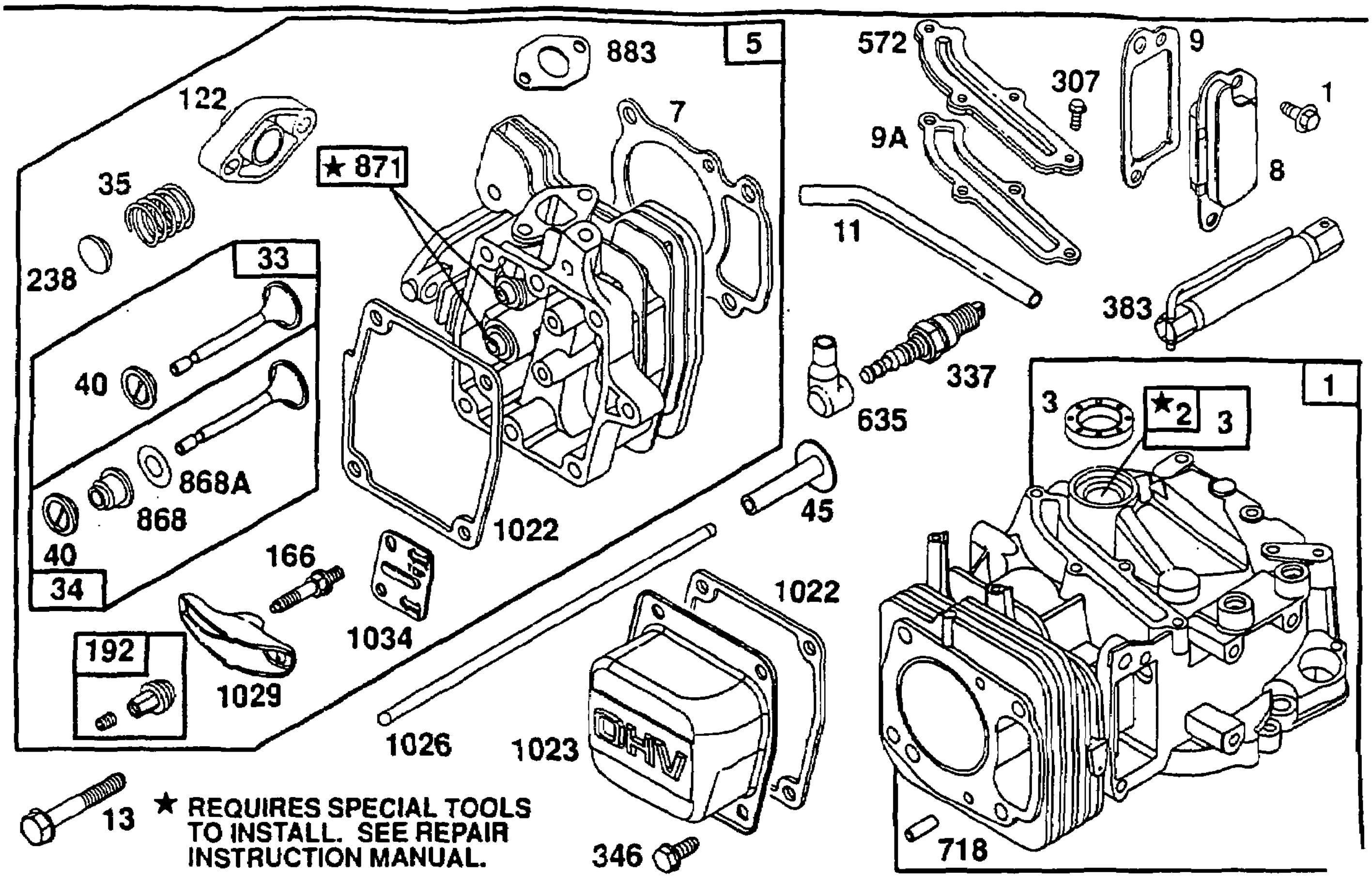


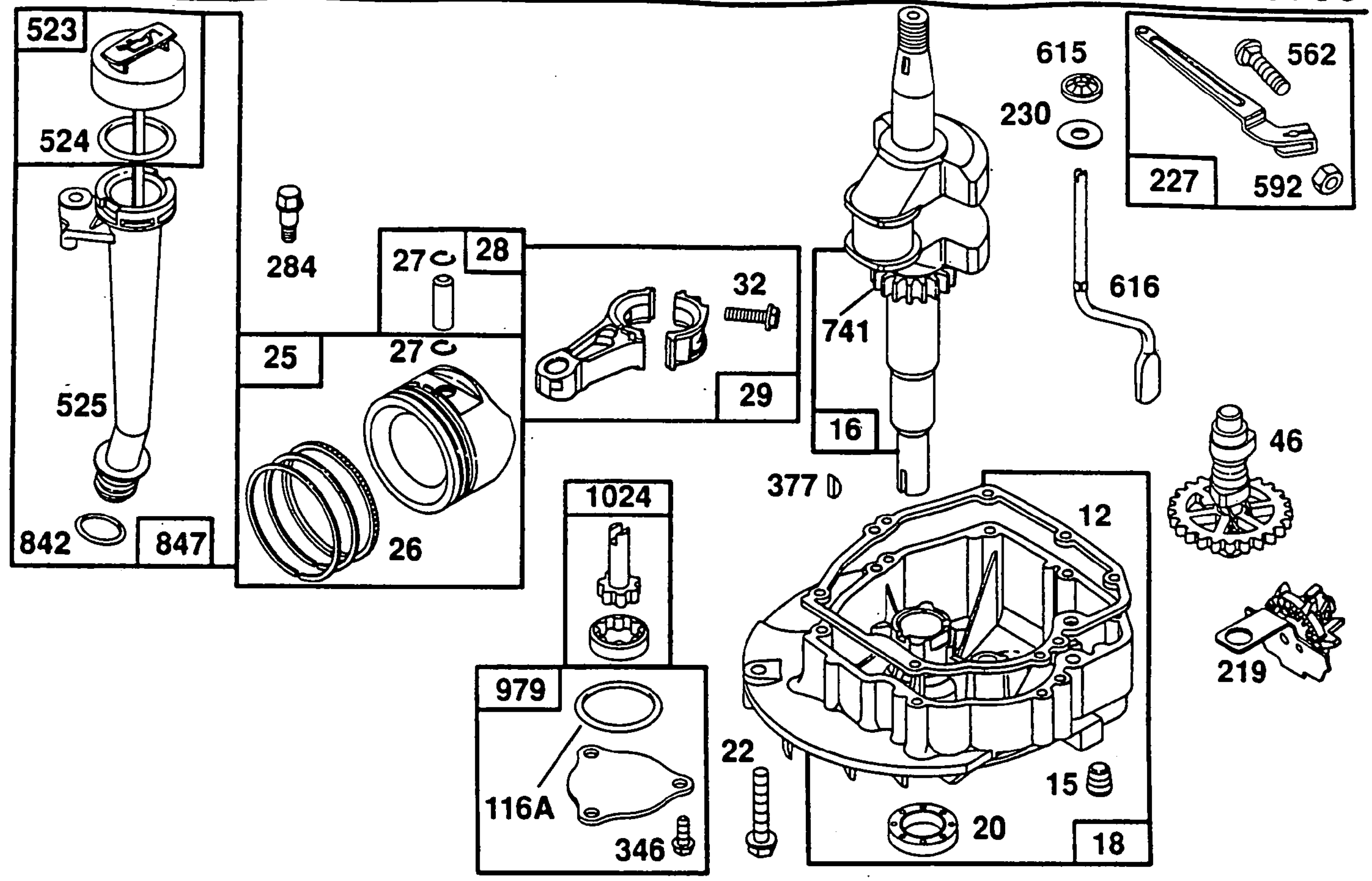
1019 LABEL KIT

1058 OWNER'S MANUAL

REF. NO.	PART NO.	DESCRIPTION
1	494728	Cylinder Assembly
2	293708	Bushing
3	★299819	*Seal–Oil*
5	496054	Head–Cylinder (Used After Code Date 92080400). ——— Note ——— 494726 Head–Cyl. (Used Before Code Date 92080500).
7		Gasket–Cylinder Head **See Last Pages.**
8	494489	Breather Assembly
9	★272481	Gasket–Breather
9A	★272238	Gasket–Breather
10	94650	Screw–Hex.
11	231933	Tube–Breather (Used After Code Date 93103100). ——— Note ——— 231685 Tube–Breather (Used Before Code Date 93110100).
13	94547	Screw–Cylinder Hd.
33	493778	Valve–Exhaust
34	493777	Valve–Intake
35	262716	Spring–Valve
40	262552	Retainer–Valve
45	262679	Tappet–Valve
122	281193	Spacer
166	94555	Stud–Rocker Arm
192	492160	Ball & Screw–Rocker Arm
238	262499	Cap–Valve
307	94515	Screw–Hex.
337	491055	Plug–Spark
346	94513	Screw–Hex.
383	19374	Wrench–Spark Plug
572	224328	Baffle–Cylinder
635	66538	Boot–Spark Plug
718	230192	Pin–Cylinder
868	★Δ493661	*Seal–Valve*
868A	★Δ272376	Gasket–Valve
871	262718	Bushing–Guide
883	★Δ272313	Gasket–Exhaust
1019	495337	Label Kit
1022	★Δ272323	Gasket–Rocker Cover
1023	224588	Cover–Rocker
1026	493527	Rod–Push
1029	224111	Arm–Rocker
1034	224400	Guide–Push Rod
1058	273123	Owner's Manual (Used After Code Date 94112000). ——— Note ——— 272520 Owner's Manual (Used Before Code Date 94112100).

★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

Assemblies include all parts shown in frames.

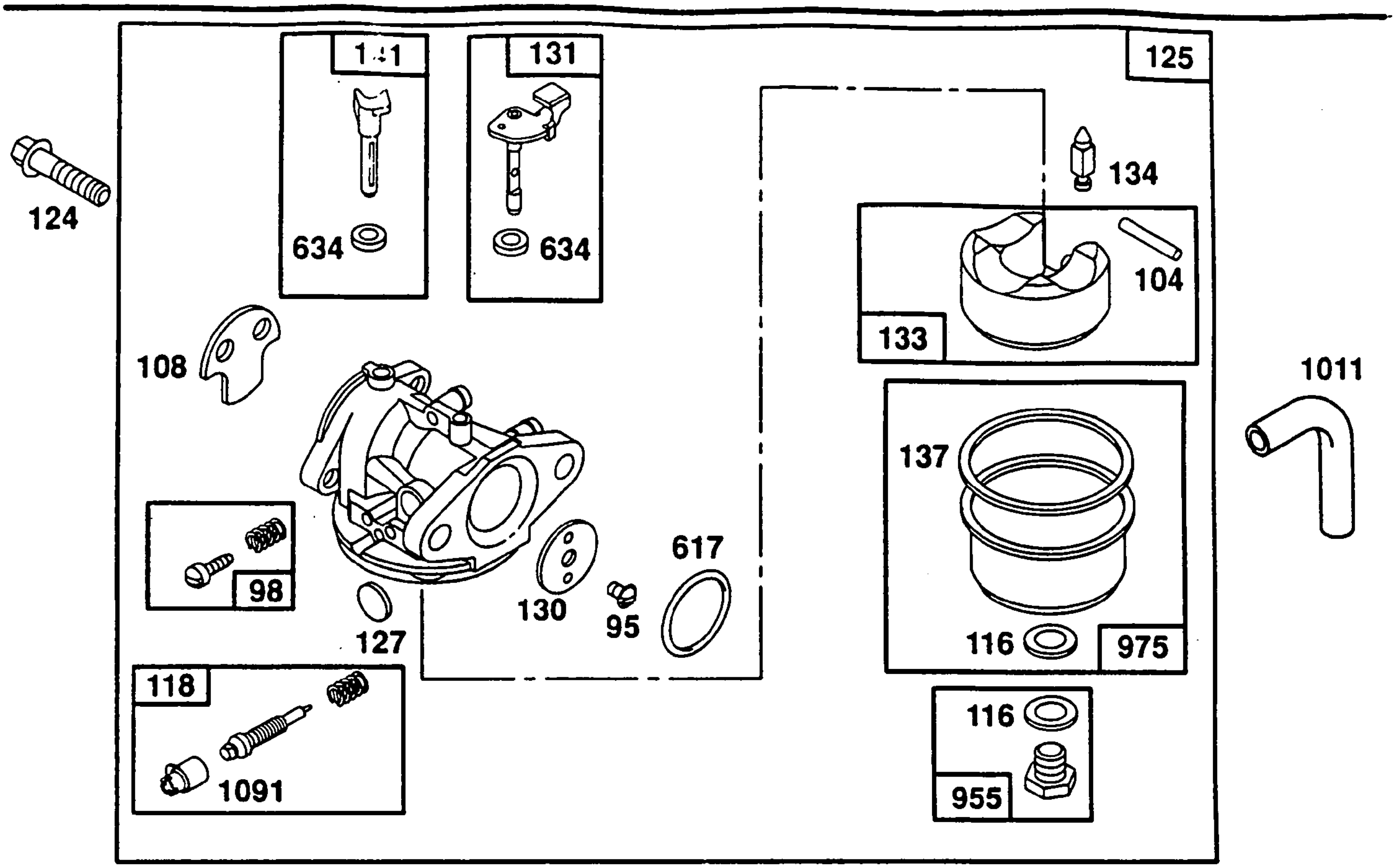


REF. NO.	PART NO.	DESCRIPTION
12	★272324	Gasket–Crankcase
15	94613	Plug–Oil Drain
16		Crankshaft **See Last Pages.**
18	493901	Sump–Engine
20	★399781	Seal–Oil
22	94220	Screw–Hex.
		—— **Note** —— 94612 Screw–Hex. One Used in Hole Nearest Breather.
25	493781	Piston Assy. (Standard)
		495267 Piston Assy. (.010 O.S.)
		495269 Piston Assy. (.020 O.S.)
		495271 Piston Assy. (.030 O.S.)
26	493782	Ring Set (Standard)
		495268 Ring Set (.010 O.S.)
		495270 Ring Set (.020 O.S.)
		495272 Ring Set (.020 O.S.)
27	262514	Lock–Piston Pin
28	492765	Pin–Piston (Standard)
29	493049	Rod–Connecting
		493689 Rod–Conn. (.020" Undersize)
32	94404	Screw–Conn. Rod
46	493310	Gear–Cam
116A	★280891	Seal–O-Ring
219	493719	Gear–Governor
227	492349	Lever–Governor
230	67072	Washer
284	94511	Screw–Hex.
346	94513	Screw–Hex.
377	93065	Key–Woodruff
523		Cap–Oil Fill **See Last Pages.**
524	★280393	Seal–Fill Tube
525		Tube–Oil Fill **See Last Pages.**
562	92613	Bolt–Carriage
592	231082	Nut–Hex.
615	94474	Pushnut
616	262578	Crank–Governor
741	262598	Gear–Timing
842	★280966	Seal–O-Ring
847		Tube–Oil **See Last Pages.**
979	492756	Cover–Oil Pump
1024	493884	Pump–Oil

★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

Assemblies include all parts shown in frames.

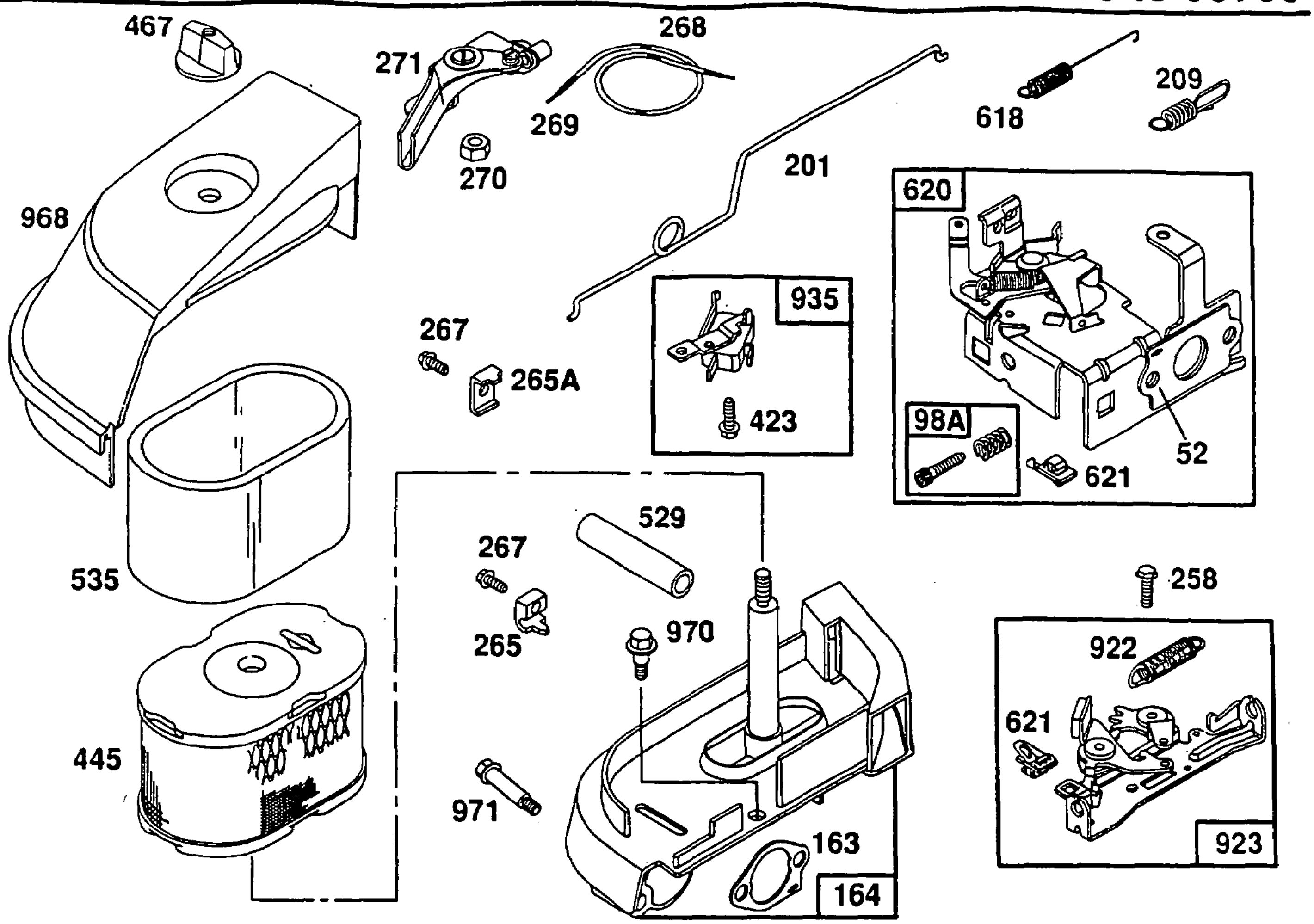
99700 to 99799



REF. NO.	PART NO.	DESCRIPTION
95	94098	Screw–Round Head
98	398185	Screw–Idle Adjustment
104	•231371	Pin–Float Hinge
108	223471	Valve–Choke
116	•◆	Gasket–Sealing (Sold in Kit Only)
118	•497717	Valve–Idle Adjust (Used After Code Date 94112000). ——— Note ——— •493765 Valve–Idle Adjust (Used Before Code Date 94112100).
124	94656	Screw–Hex.
125	497718	Carburetor (Used After Code Date 94112000). 494971 Carburetor (Used Before Code Date 94112100).
127	•	Plug–Welch (Sold in Kit Only)
130	223470	Valve–Throttle
131	493267	Shaft–Throttle
133	398187	Float–Carburetor
134	•398188	Valve–Needle (Includes Seat)
137	•◆	Gasket–Float Bowl (Sold in Kit Only)
141	494218	Shaft–Choke
617	•◆270344	Seal–Intake Elbow
634	•◆	Washer–Shaft (Sold in Kit Only)
955	494870	Screw–Fuel Bowl (Standard) ——— Note ——— 496495 Screw–Fuel Bowl (High Altitude)
975	493640	Bowl–Float
1011	281244	Tube–Vent
1091	•281425	Cap–Limiter (Used After Code Date 94112000).

★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
• Included in Carburetor Kit–See Ref. No. 121.

Assemblies include all parts shown in frames.

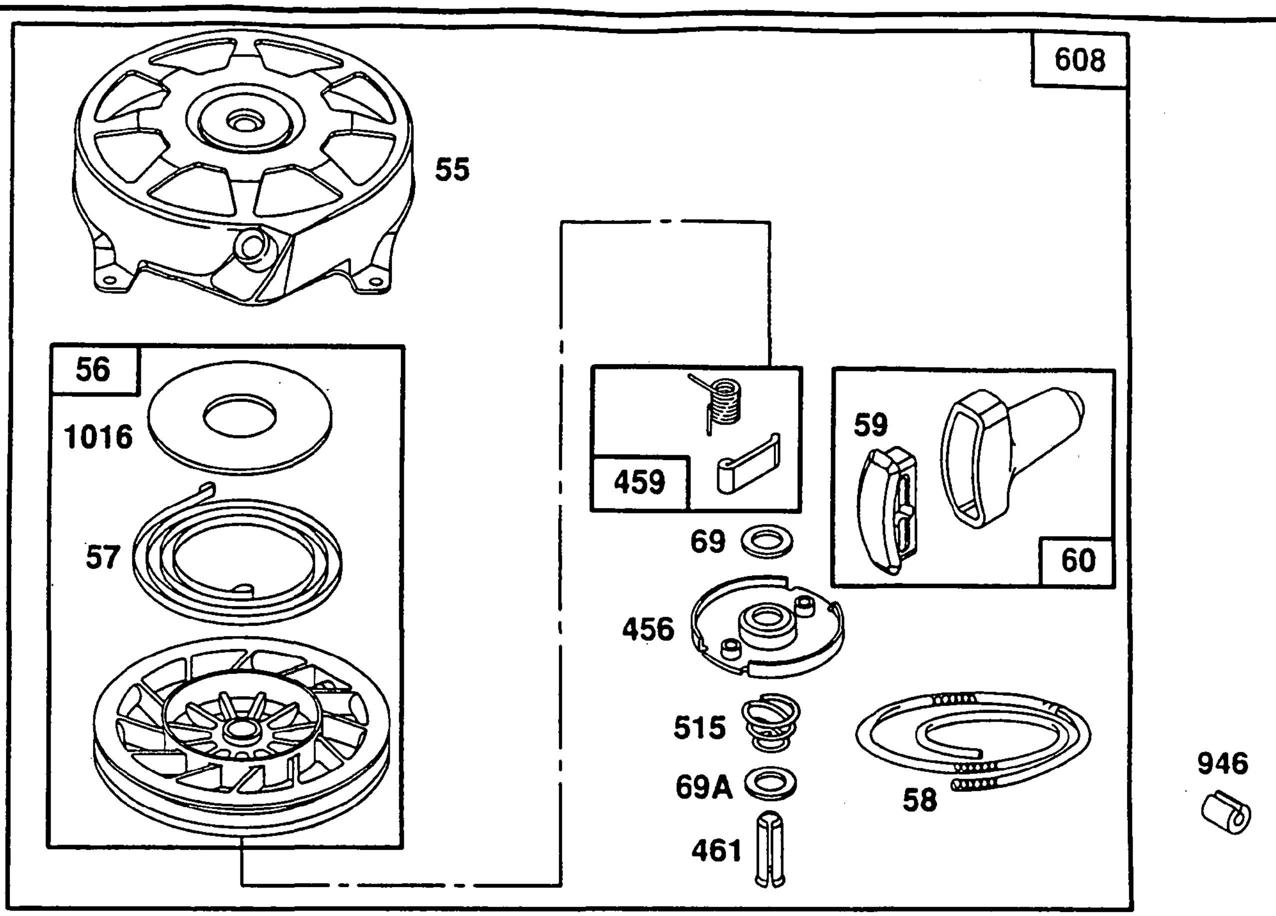


REF. NO.	PART NO.	DESCRIPTION
52	★Δ272487	Gasket–Intake
98A	493280	Screw Assy.– Speed Adjustment
163	★272512	Gasket–Air Cleaner
164	494729	Manifold–Intake
201	262827	Link
209		Spring–Governor **See Last Pages.**
265	213146	Clamp–Casing
265A	221535	Clamp–Casing
267	94694	Screw–Hex.
258	94512	Screw–Hex.
268	66986	Casing–Wire (48" Long) —— Note —— If Longer Casing is Needed, Specify Length in Inches; if Shorter Casing is Needed Order and Cut to Required Length.
269	26099	Wire–Control (54" Long) —— Note —— If Longer Wire is Needed, Specify Length in Inches; if Shorter Wire is Needed Order and Cut to Required Length.
270	63426	Locknut–Casing
271	290568	Lever–Control
423	93758	Screw
445	494586	Filter–Air
467	493903	Knob
529	281418	Grommet (Used After Code Date 93101700). —— Note —— 281201 Grommet (Used Before Code Date 93101800).
535	272533	Filter–Air
618	262749	Spring
620	494538	Bracket–Control
621	396847	Switch–Stop
922	262640	Spring–Brake
923	493442	Brake
935	398758	Switch–Interlock
968	281196	Cover–Air Cleaner
970	94577	Screw–Air Cleaner
971	94655	Screw–Shoulder

★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

Assemblies include all parts shown in frames.

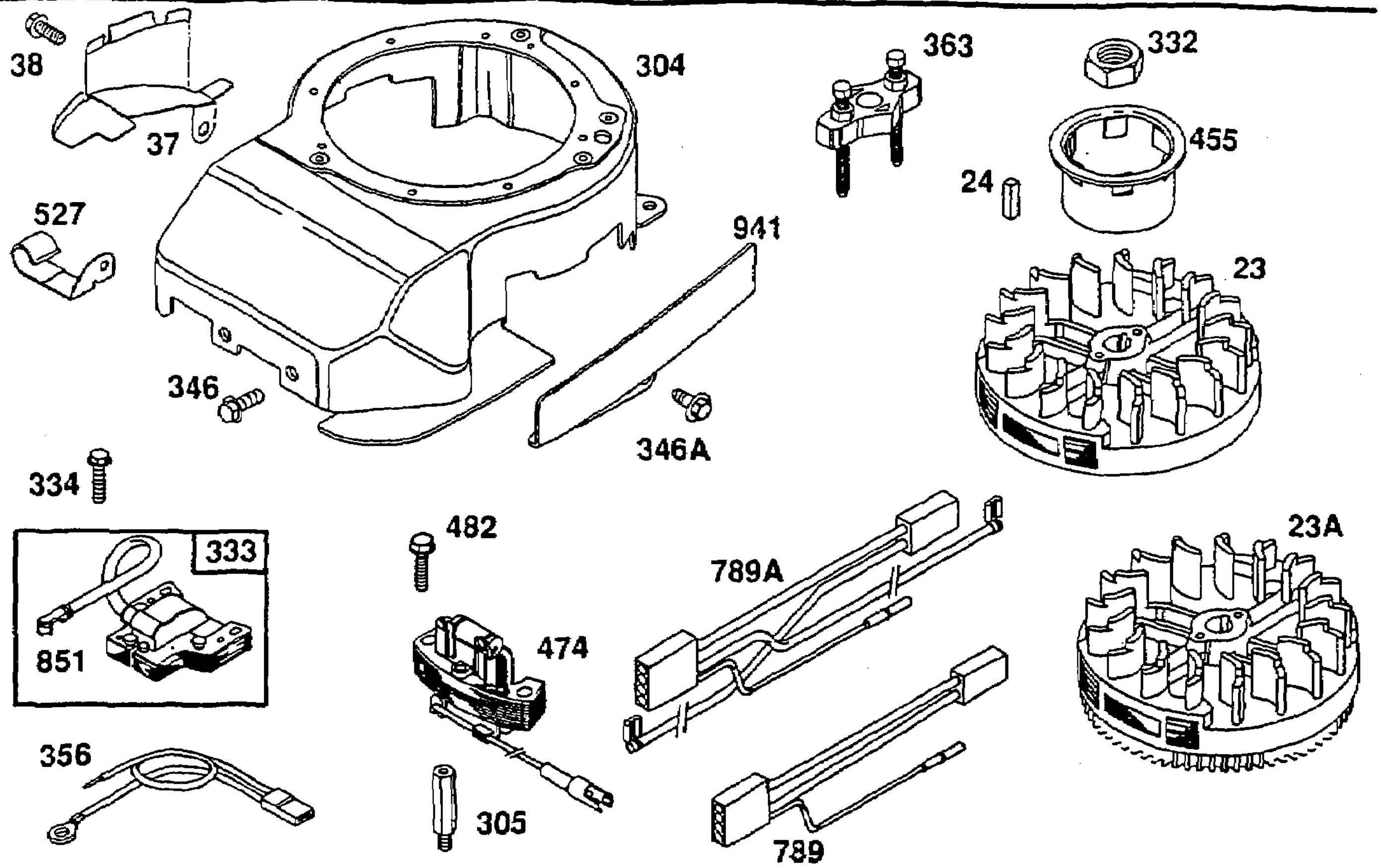
99700 to 99799



REF. NO.	PART NO.	DESCRIPTION
55	494671	Housing-Rewind Starter
56	493824	Pulley-Starter
57	262594	Spring-Rewind Starter
58	280399	Rope-Starter (Cut to 88-5/8")
59	396892	Insert-Handle
60	393152	Grip-Starter Rope
69	280973	Washer-Spring
69A	224322	Washer-Flat
456	224321	Retainer-Spring
459	492833	Pawl-Ratchet
461	262626	Pin-Shaft
515	262625	Spring-Retainer
608	494960	Starter-Rewind **Include(s):** 92987 Nut-Hex 94128 Screw-Hex.
946	223294	Guide-Rope
1016	224278	Spacer

★ Included in Gasket Set-See Ref. No. 358.
Δ Included in Valve Overhaul Kit-See Ref. No. 1033.
◆ Included in Carburetor Gasket Set-Part No. 490937.
● Included in Carburetor Kit-See Ref. No. 121.

Assemblies include all parts shown in frames.

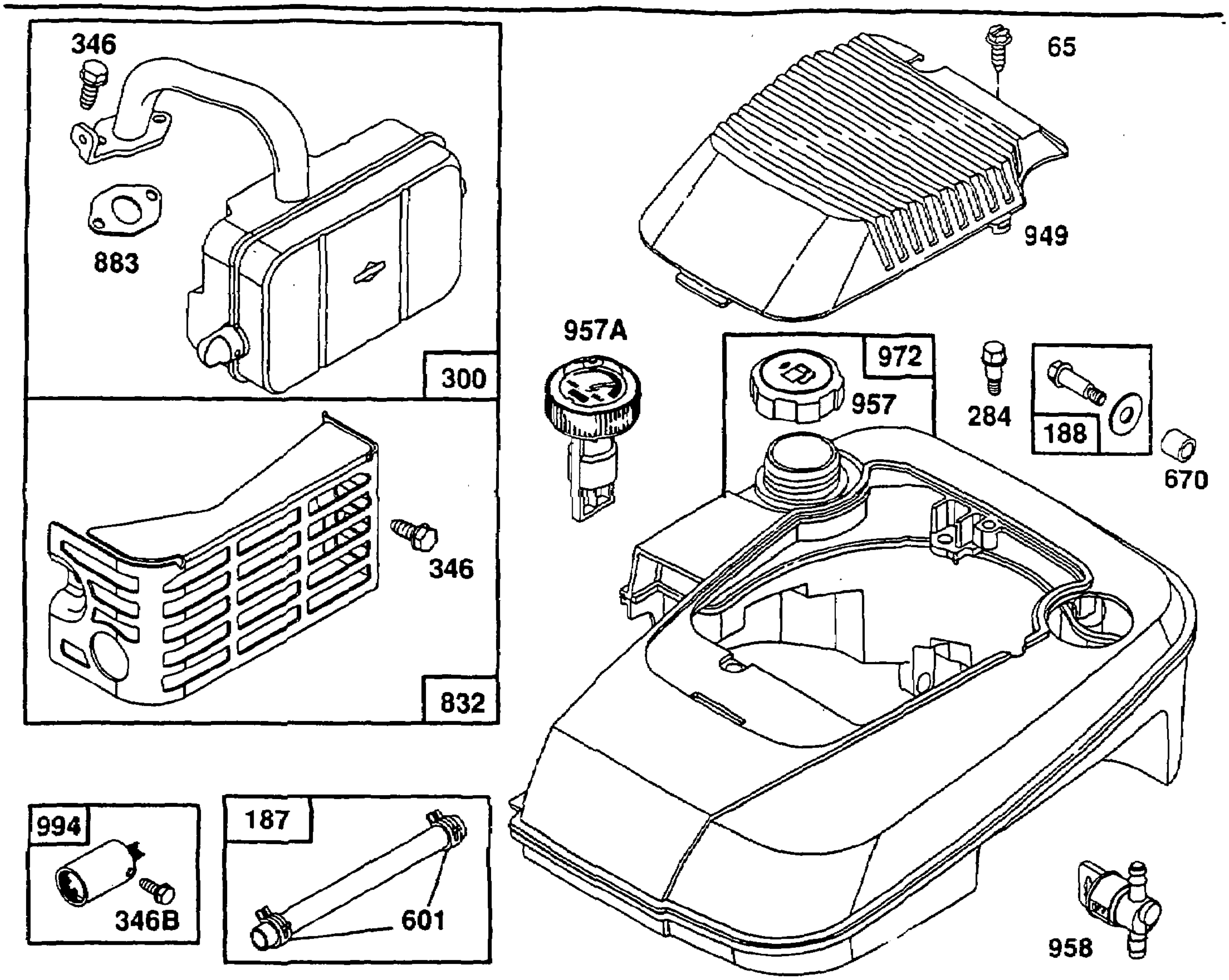


REF. NO.	PART NO.	DESCRIPTION
23	492177	Flywheel
23A	492175	Flywheel
		—— Note ——
		492893 Flywheel Used on Type No(s). 0625, 0626, 0636, 0925.
24	222698	Key–Flywheel
37	224511	Guard–Flywheel
38	94608	Screw–Hex.
304	494961	Housing–Blower Used on Engines With Band Brake.
		—— Note ——
		494962 Housing–Blower Used on Engines Without Band Brake.
305	94510	Stud–Stator Mtg.
332	92284	Nut–Flywheel
333	802574	Armature–Magneto
334	93381	Screw–Hex.
346	94513	Screw–Hex.
346A	94582	Screw–Hex.
356	398808	Wire–Stop
		—— Note ——
		496381 Wire–Stop (Used After Code Date 93080300).
		398153 Wire–Stop (Used Before Code Date 93080400). Used on Type No(s). 0110, 0610, 3111, 3611, 3624.
		496721 Wire–Stop Used on Type No(s). 0625.
363	19069	Flywheel Puller
455	224250	Cup–Flywheel
474	492841	Alternator
482	94512	Screw–Hex.
527	224722	Clamp–Tube
789	494543	Harness–Wiring Used on Engines Without Band Brake.
789A	494544	Harness–Wiring Used on Engines With Band Brake Except as Listed Below:
		—— Note ——
		493380 Harness–Wiring Used on Type No(s). 0916, 3616.
851	221798	Terminal–Cable
941	281206	Cover–Linkage

★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

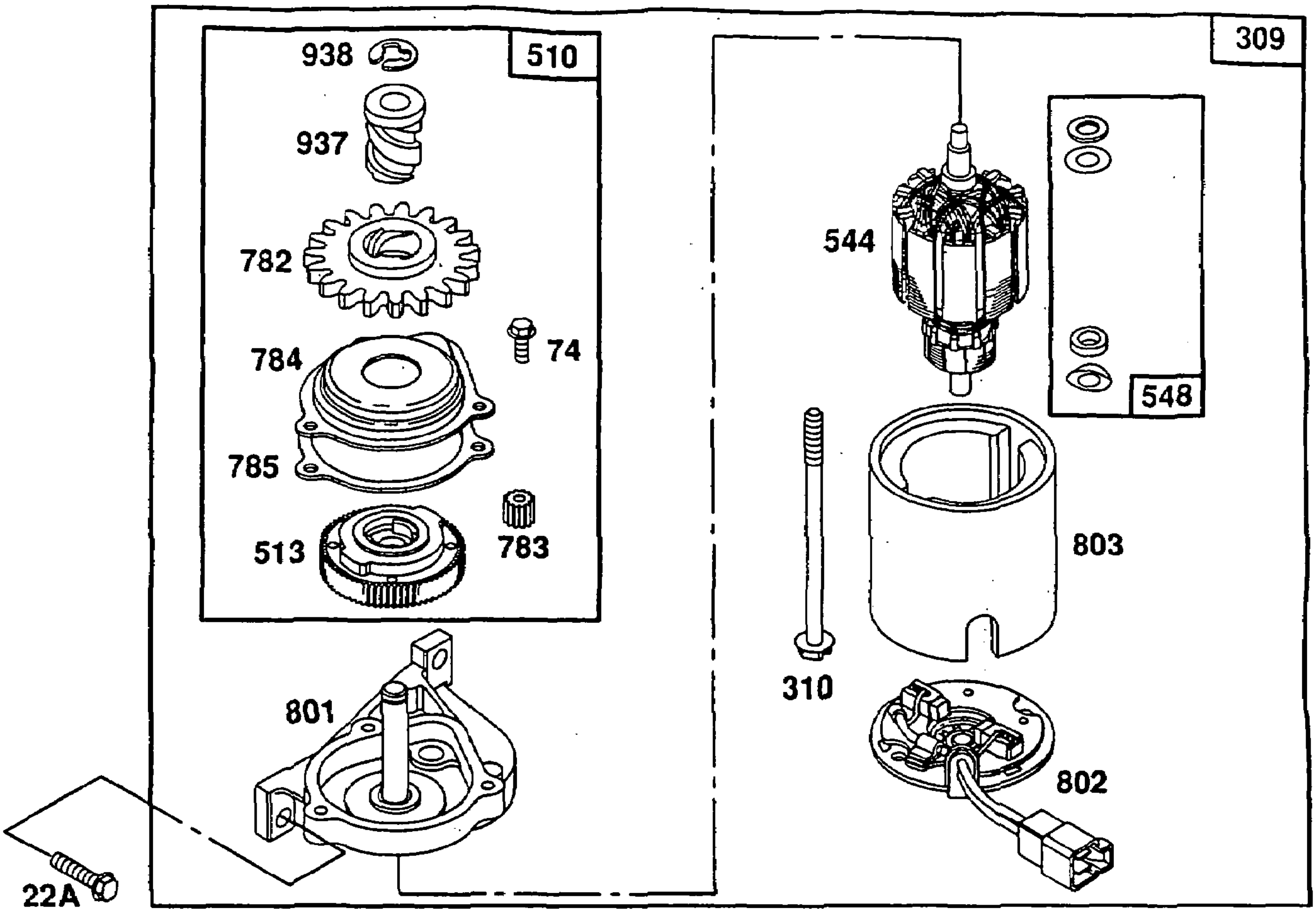
Assemblies include all parts shown in frames.

99700 to 99799



REF. NO.	PART NO.	DESCRIPTION
65	94058	Screw-Guard Mounting
187	296004	Line-Fuel (23" Long Cut to Suit)
		——— Note ———
		393815 Line-Fuel (11" Long Cut to Suit)
188	398540	Screw-Tank Mounting
284	94511	Screw-Shoulder
300	494717	Muffler-Exhaust
346	94513	Screw-Hex.
346B	93705	Screw-Hex.
601	93053	Clamp-Hose
670	280512	Spacer-Fuel Tank
832	494719	Guard-Muffler
883	★Δ272313	Gasket-Exhaust
949	281197	Guard-Starter
		——— Note ———
		281406 Guard-Starter Used on Type No(s). 0632, 0633, 0634, 0636, 0637, 0638, 0814, 0916, 0918, 0920, 0925, 0934, 0935, 0937, 0938, 0942, 0945, 3114, 3141, 3142, 3616, 3620, 3625, 3641, 3642, 3650.
957	397974	Cap-Fuel Tank
957A	494277	Cap-Fuel Tank
958	493960	Valve-Shut-Off
972	494973	Tank-Fuel
994	493662	Arrester-Spark

★ Included in Gasket Set-See Ref. No. 358.
Δ Included in Valve Overhaul Kit-See Ref. No. 1033.
◆ Included in Carburetor Gasket Set-Part No. 490937.
● Included in Carburetor Kit-See Ref. No. 121.

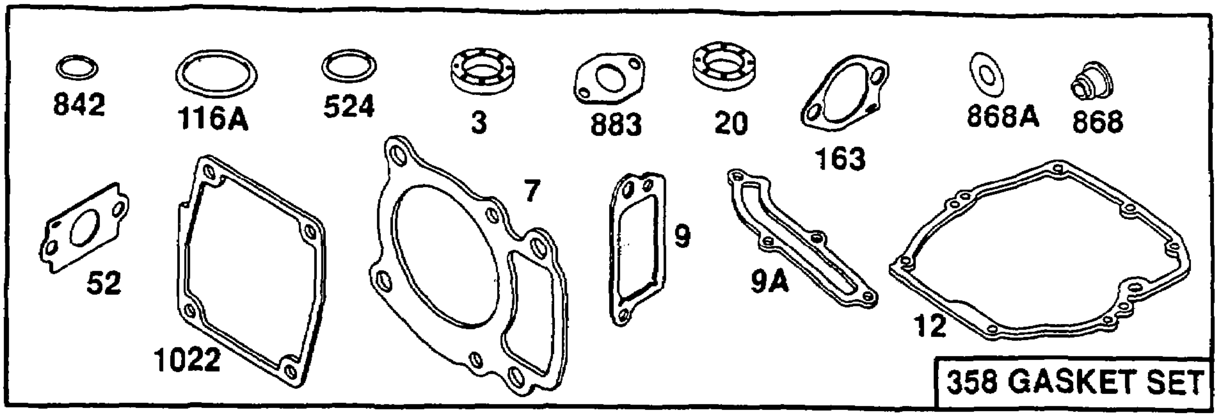


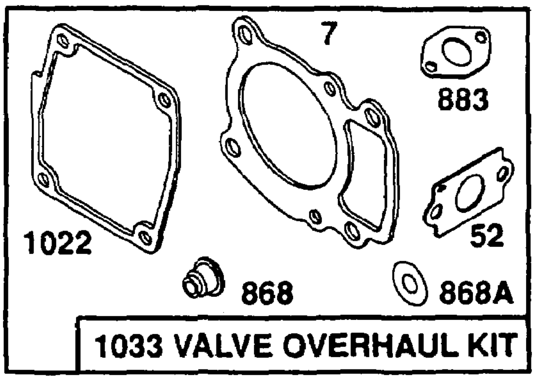
REF. NO.	PART NO..	DESCRIPTION
22A	94268	Screw–Hex.
74	93490	Screw–Hex.
309	494233	Motor–Starter
310	94051	Screw–Hex.
510	494147	Drive–Starter
513	394815	Clutch–Drive
544	492921	Armature–Starter
548	492919	Washer Set
782	281127	Gear–Starter
783	261606	Gear–Starter
784	224262	Cover–Gear
785	272201	Gasket–Cover
801	492335	Cap–Drive
802	492922	Cap–End
803	492920	Housing–Starter
937	281125	Spline–Starter
938	93941	Retainer–Lock

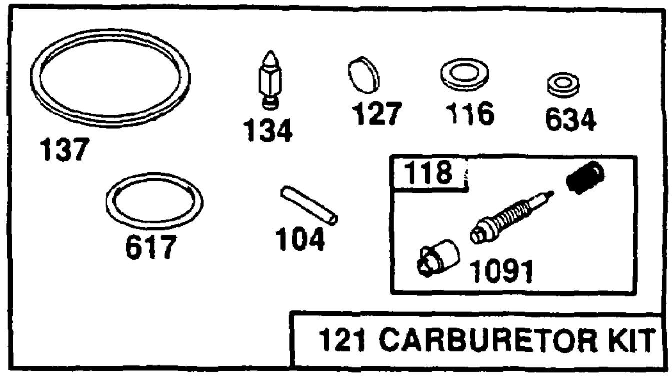
★ Included in Gasket Set–See Ref. No. 358.
Δ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

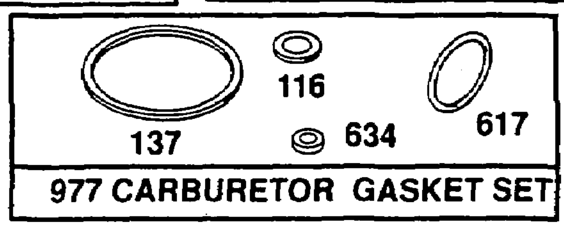
Assemblies include all parts shown in frames.

99700 to 99799









REF. NO.	PART NO.	DESCRIPTION
3	★299819	Seal-Oil
7		Gasket-Cylinder Head **See Last Pages.**
9	★272481	Gasket-Breather
9A	★272238	Gasket-Breather
12	★272324	Gasket-Crankcase
20	★399781	Seal-Oil
52	★Δ272487	Gasket-Intake
104	•231371	Pin-Float Hinge
116	•◆	Gasket-Sealing (Sold in Kit Only)
116A	★280891	Seal-O-Ring
118	•497717	Valve-Idle Adjust (Used After Code Date 94112000).

REF. NO.	PART NO.	DESCRIPTION
		——— Note ——— •493765 Valve-Idle Adjust (Used Before Code Date 94112100).
121	497719	Carburetor Kit (Used After Code Date 94112000). 493762 Carburetor Kit (Used Before Code Date 94112100).
127	•	Plug-Welch (Sold in Kit Only)
134	•398188	Valve-Needle (Includes Seat)
137	•◆	Gasket-Float Bowl (Sold in Kit Only)
163	★272512	Gasket-Air Cleaner

REF. NO.	PART NO.	DESCRIPTION
358		Gasket Set **See Last Pages.**
524	★280393	Seal-Fill Tube
617	•◆270344	Seal-Intake Elbow
634	•◆	Washer-Shaft (Sold in Kit Only)
842	★280966	Seal-O-Ring
868	★Δ493661	Seal-Valve
868A	★Δ272376	Gasket-Valve
883	★Δ272313	Gasket-Exhaust
977	490937	Gasket Set-Carburetor
1022	★Δ272323	Gasket-Rocker Cover
1091	•281425	Cap-Limiter (Used After Code Date 94112000).
1033		Kit-Valve Overhaul **See Last Pages.**

★ Included in Gasket Set-See Ref. No. 358.
Δ Included in Valve Overhaul Kit-See Ref. No. 1033.
◆ Included in Carburetor Gasket Set-Part No. 490937.
• Included in Carburetor Kit-See Ref. No. 121.

Assemblies include all parts shown in frames.

REF. NO.	PART NO.	DESCRIPTION
7	★∆272314	Gasket–Cylinder Head (Used After Code Date 92080400).
		— Note —
		★∆272488 Gasket–Cylinder Head (Used Before Code Date 92080500).
16	494638	Crankshaft
		— Note —
		For Timing Gear Key–Order Part No. 94388.
		493725 Crankshaft Used on Type No(s). 0638, 0938.
		494635 Crankshaft Used on Type No(s). 0118, 3025, 3111.
		494636 Crankshaft Used on Type No(s). 0114, 3024, 3114, 3141, 3142.
		494637 Crankshaft Used on Type No(s). 0100, 0102, 0103, 0112, 0116, 3015, 3101, 3103, 3120, 3143.
		494639 Crankshaft Used on Type No(s). 0110, 0111, 0115, 3026.
		495515 Crankshaft Used on Type No(s). 0623.
		495793 Crankshaft Used on Type No(s). 0618, 0622, 0633, 0918, 0945, 3525, 3611, 3617, 3624, 3625.
		495794 Crankshaft Used on Type No(s). 3641.
		495795 Crankshaft Used on Type No(s). 0612, 0625, 0626, 0630, 0636, 0916, 0920, 0925, 0935, 0942, 3515, 3601, 3608, 3616, 3620, 3642, 3643.
		495796 Crankshaft Used on Type No(s). 0601, 0606, 0614, 0619, 0621, 0632, 0634, 0814, 0934, 3612, 3613, 3650.
		495797 Crankshaft Used on Type No(s). 0610, 0611, 0615, 0624, 0637, 0937.
209	262678	Spring–Governor
		— Note —
		262657 Spring–Gov. Used on Type No(s). 0110, 0610, 0625, 0925, 0945, 3111, 3611, 3617, 3624, 3625.
		262659 Spring–Gov. Used on Type No(s). 0100, 0103, 0626, 0636, 0942, 3015, 3016, 3024, 3025, 3026, 3101, 3103, 3114, 3141, 3142, 3515, 3525, 3601, 3608, 3641, 3642.
		262660 Spring–Gov. Used on Type No(s). 3143, 3643.
		262661 Spring–Gov. Used on Type No(s). 0638, 0938.
		262665 Spring–Gov. Used on Type No(s). 0115, 0615, 0637, 0937,3112, 3113, 3612, 3613.
		262666 Spring–Gov. Used on Type No(s). 0116, 0619, 0622.
		262667 Spring–Gov. Used on Type No(s). 0633, 0916, 0920, 3120, 3616, 3620.
		262678 Spring–Gov. Used on Type No(s). 0632, 0634, 0814, 0918, 0934, 0935, 3650.
358	496055	Gasket Set (Used After Code Date 92080400).
		— Note —
		494963 Gasket Set (Used Before Code Date 92080500).
523	495264	Cap–Oil Fill (Used After Code Date 92083000).
		— Note —
		493950 Cap–Oil Fill (Used Before Code Date 92083100).
525	495265	Tube–Oil Fill (Used After Code Date 92083000).
		— Note —
		493952 Tube–Oil Fill (Used Before Code Date 92083100).
847	495263	Tube–Oil Fill (Used After Code Date 92083000).
		— Note —
		493459 Tube–Oil (Used Before Code Date 92083100).
1033	496056	Overhaul Kit–Valve (Used After Code Date 92080400).
		— Note —
		495772 Overhaul Kit–Valve (Used After Code Date 92080500).

★ Included in Gasket Set–See Ref. No. 358.
∆ Included in Valve Overhaul Kit–See Ref. No. 1033.
◆ Included in Carburetor Gasket Set–Part No. 490937.
● Included in Carburetor Kit–See Ref. No. 121.

General Purpose Engine
GXV140

HONDA
Power
Equipment

Parts Catalog

First Edition

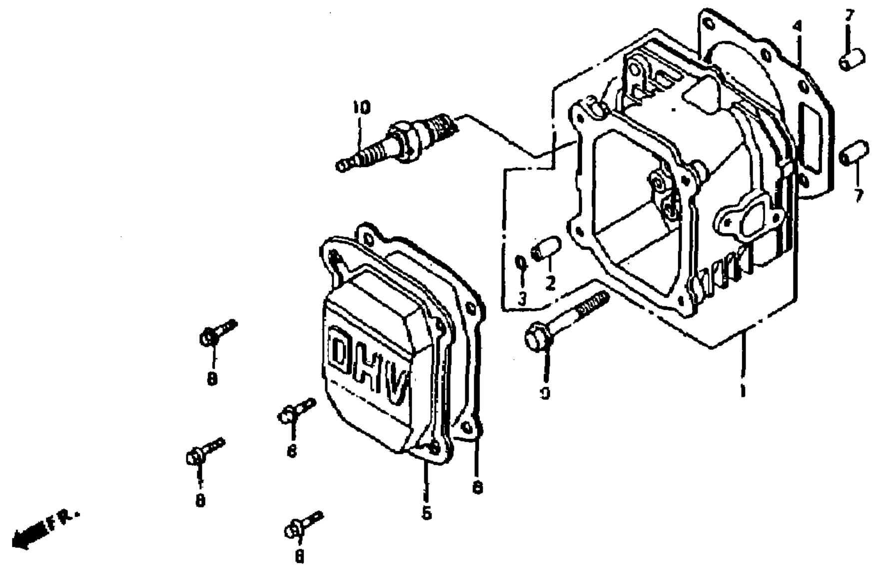
May, 1994

AMERICAN HONDA MOTOR CO., INC.

14ZG90E1

PRINTED IN USA

CYLINDER HEAD

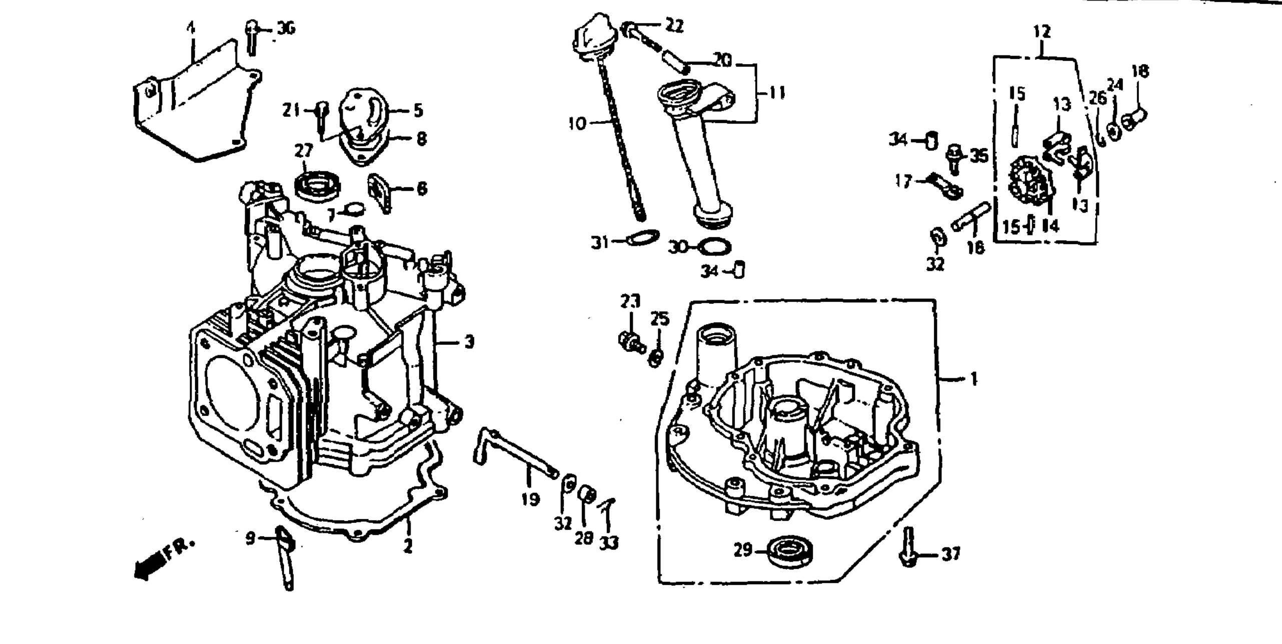


GXV140

BLOCK NO. E-2

Ref. No.	DESCRIPTION	TYPE A1 a	TYPE A2 b	TYPE N1 c	TYPE N2 d	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
1	HEAD COMP, CYLINDER	a	b	c	d	-------	-------	1	12200-ZG9-800	4452470
2	GUIDE, EX. VALVE (OVER SIZE)	a	b	c	d	-------	-------	(1)	12205-ZE1-315	1899848
3	CLIP, VALVE GUIDE	a	b	c	d	-------	-------	1	12216-ZE5-300	2399780
4	GASKET, CYLINDER HEAD	a	b	c	d	-------	-------	1	12251-ZG9-000	3337821
5	COVER, HEAD	a	b	c	d	-------	-------	1	12311-ZG9-800	4428165
6	GASKET, HEAD COVER	a	b	c	d	-------	-------	1	12391-ZE7-T00	4311437
7	PIN A, DOWEL, 10X16	a	b	c	d	-------	-------	2	94301-10160	0058206
8	BOLT, FLANGE, 6X14	a	b	c	d	-------	-------	4	95701-06014-00	2410884
9	BOLT, FLANGE, 8X50	a	b	c	d	-------	-------	4	95701-08050-00	2935740
10	PLUG, SPARK (BP4ES NGK)	a	b	c	d	-------	-------	(1)	98079-54841	1455427
	PLUG, SPARK (BPR4ES NGK)	a	b	c	d	-------	-------	(1)	98079-54846	1521756
	PLUG, SPARK (BPR5ES NGK)	a	b	c	d	-------	-------	1	98079-55846	1672443
	PLUG, SPARK (BPR6ES NGK)	a	b	c	d	-------	-------	(1)	98079-56846	1441112

CYLINDER BARREL



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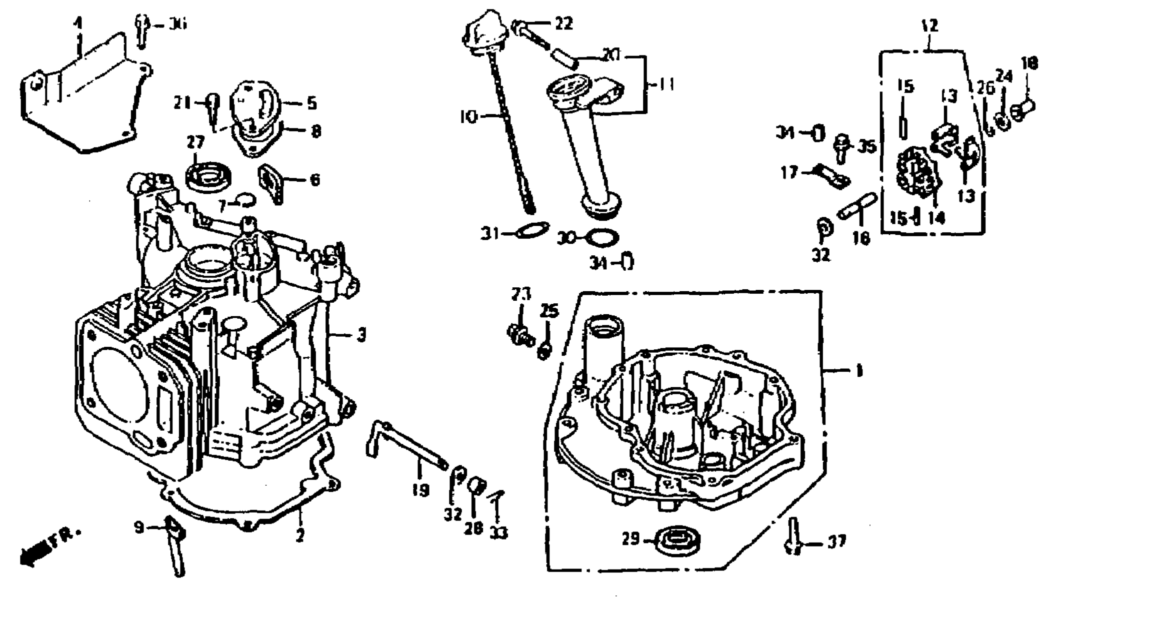
GXV140

Ref. No.	BLOCK NO. E-3 DESCRIPTION	TYPE A1 a	A2 b	N1 c	N2 d	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
	AYP								11310-[illegible]	4722591
1	PAN ASSY., OIL (USA-PUSH)	a	b	c	d	-------	-------	1	11300-ZG9-800	4536934
2	GASKET, OIL PAN	a	b	c	d	-------	-------	1	11381-ZG9-T00	4224259
3	BARREL COMP., CYLINDER	a	b	c	d	-------	-------	1	12100-ZG9-800	4459491
4	PLATE, GUIDE	a	b	c	d	-------	-------	1	12125-ZG9-000	3307287
5	CAP COMP., BREATHER CHAMBER	a	b	c	d	-------	-------	1	12360-ZE6-000	1662535
6	FILTER, BREATHER	a	b	c	d	-------	-------	1	12367-ZE6-010	2794402
7	VALVE, BREATHER	a	b	c	d	-------	-------	1	12372-879-000	0452151
8	GASKET, BREATHER CHAMBER	a	b	c	d	-------	-------	1	12373-ZE6-000	1452622
9	PIPE, OIL DEFENSE	a	b	c	d	-------	-------	1	12385-ZE6-000	1825702
10	GAUGE COMP., OIL LEVEL	a	b	c	d	-------	-------	1	15620-ZE6-810	3337862
11	EXTENSION, OIL FILLER	a	b	c	d	-------	-------	1	15630-ZE6-810	3337870
12	GOVERNOR ASSY.	a	b	c	d	-------	-------	1	16510-ZE6-000	3337904
13	WEIGHT, GOVERNOR	a	b	c	d	-------	-------	2	16511-ZE1-000	1427228
14	HOLDER, GOVERNOR WEIGHT	a	b	c	d	-------	-------	1	16512-ZE6-000	1452846
15	PIN, GOVERNOR WEIGHT	a	b	c	d	-------	-------	2	16513-ZE1-000	1427244
16	SHAFT, GOVERNOR HOLDER	a	b	c	d	-------	-------	1	16515-ZE6-000	1452853

CYLINDER BARREL



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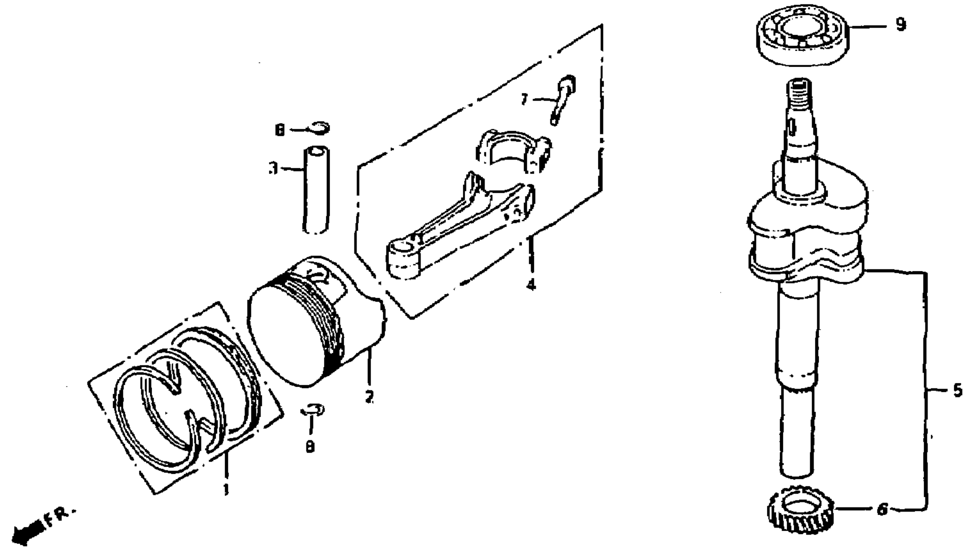
GXV140

Ref. No.	BLOCK NO. E-3 DESCRIPTION	TYPE A1 a	A2 b	N1 c	N2 d	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
17	PLATE, GOVERNOR SHAFT HOLDER	a	b	c	d	--------	--------	1	16525-ZE6-010	3337912
18	SLIDER, GOVERNOR	a	b	c	d	--------	--------	1	16531-ZE1-000	1427251
19	SHAFT, GOVERNOR ARM	a	b	c	d	--------	--------	1	16541-ZE7-000	2289643
20	COLLAR, EXTENSION	a	b	c	d	--------	--------	1	17240-ZE6-000	1453000
21	BOLT, FLANGE, 6X14	a	b	c	d	--------	--------	2	90014-952-000	0803619
22	BOLT, FLANGE, 6X32	a	b	c	d	--------	--------	1	90017-883-000	0636076
23	BOLT, DRAIN PLUG	a	b	c	d	--------	--------	1	90131-ZE1-000	1431246
24	WASHER, THRUST, 6MM	a	b	c	d	--------	--------	1	90451-ZE1-000	2413862
	WASHER, THRUST, 6MM	a	b	c	d	--------	--------	1	90451-898-000	1106764
25	WASHER, DRAIN PLUG, 10.2MM	a	b	c	d	--------	--------	1	90601-ZE1-000	1436583
26	CLIP, GOVERNOR HOLDER	a	b	c	d	--------	--------	1	90602-ZE1-000	2456697
27	OIL SEAL, 22X35X6	a	b	c	d	--------	--------	1	91202-ZE6-003	3270246
28	SEAL, OIL, 6X11X4	a	b	c	d	--------	--------	1	91231-891-003	0801043
29	OIL SEAL, 25X38X7 (ARAI)	a	b	c	d	--------	--------	1	91252-888-003	0671628
30	O-RING, 22.5X2.2	a	b	c	d	--------	--------	1	91301-ZE9-003	2280006
31	O-RING, 26X2.7	a	b	c	d	--------	--------	1	91301-805-000	0065185

CRANKSHAFT



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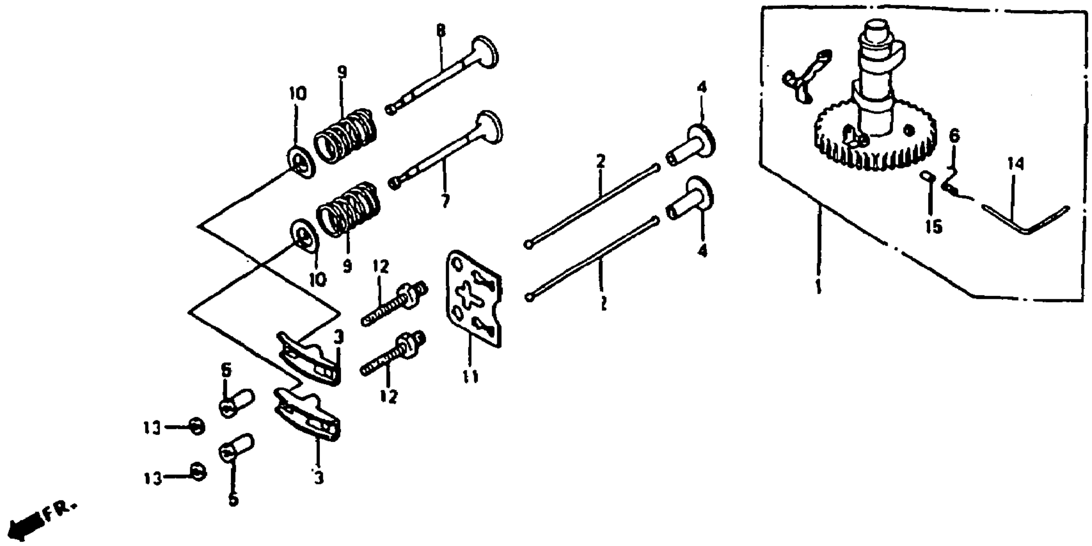
Ref. No.	DESCRIPTION (BLOCK NO. E-7)	A1 a	A2 b	N1 c	N2 d	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	RING SET, PISTON (STD.)	a	b	c	d	-------	-------	1	13010-ZG9-T01	4222303
	RING SET, PISTON (0.25)	a	b	c	d	-------	-------	(1)	13011-ZG9-T01	4222311
	RING SET, PISTON (0.50)	a	b	c	d	-------	-------	(1)	13012-ZG9-T01	4222329
	RING SET, PISTON (0.75)	a	b	c	d	-------	-------	(1)	13013-ZG9-T01	4222337
2	PISTON (STD)	a	b	c	d	-------	-------	1	13101-ZG9-000	3307303
	PISTON (0.25)	a	b	c	d	-------	-------	(1)	13102-ZG9-000	3613767
	PISTON (0.50)	a	b	c	d	-------	-------	(1)	13103-ZG9-000	3613775
	PISTON (0.75)	a	b	c	d	-------	-------	(1)	13104-ZG9-000	3613783
3	PIN, PISTON	a	b	c	d	-------	-------	1	13111-ZE0-000	1426576
4	ROD ASSY., CONNECTING	a	b	c	d	-------	-------	1	13200-ZE6-010	3214913
5	CRANKSHAFT COMP.	a	b	-	-	-------	-------	1	13310-ZG9-800	4428819
	CRANKSHAFT COMP.	-	-	c	d	-------	-------	1	13310-ZG9-810	4540639
6	GEAR, TIMING	a	b	c	d	-------	-------	1	14311-ZE6-300	1452705
7	BOLT, CONNECTING ROD	a	b	c	d	-------	-------	2	90001-ZE1-000	1431055
8	CLIP, PISTON PIN, 13MM	a	b	c	d	-------	-------	2	90551-ZE0-000	2605517
9	BEARING, RADIAL BALL, 62/22	a	b	c	d	-------	-------	1	91001-878-003	0442061

CAMSHAFT



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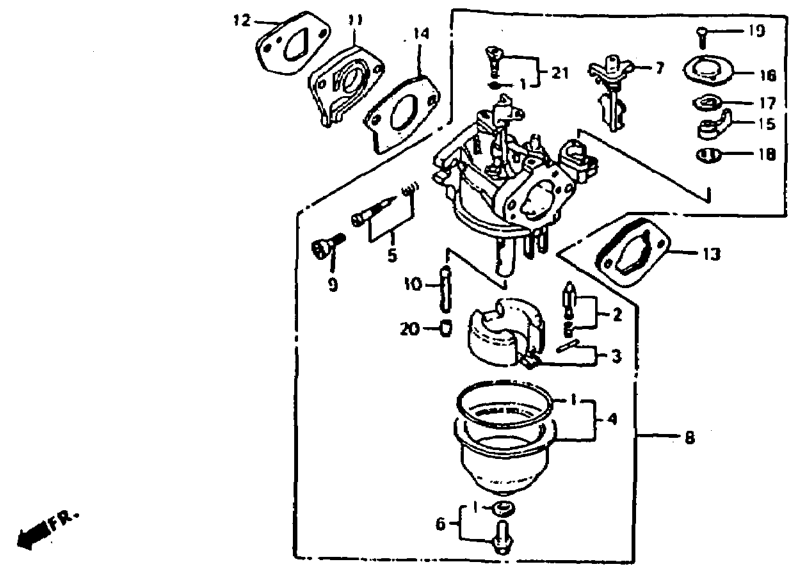
GXV140

Ref. No.	BLOCK NO. E-9 DESCRIPTION	TYPE A1 a	A2 b	N1 c	N2 d	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	CAMSHAFT ASSY.	a	b	c	d	-------	-------	1	14100-ZG9-800	4327334
2	ROD, PUSH	a	b	c	d	-------	-------	2	14410-ZE0-010	3337854
3	ARM, VALVE ROCKER	a	b	c	d	-------	-------	2	14431-ZE1-000	1426824
4	LIFTER, VALVE	a	b	c	d	-------	-------	2	14441-ZE1-000	1426832
5	PIVOT, ROCKER ARM	a	b	c	d	-------	-------	2	14451-ZE1-013	4300901
6	SPRING, WEIGHT RETURN	a	b	c	d	-------	-------	1	14568-ZG9-800	4327342
7	VALVE, IN.	a	b	c	d	-------	-------	1	14711-ZG9-801	4428454
8	VALVE, EX.	a	b	c	d	-------	-------	1	14721-ZG9-801	4428462
9	SPRING, VALVE	a	b	c	d	-------	-------	2	14751-ZF1-000	3683489
10	RETAINER, VALVE SPRING	a	b	c	d	-------	-------	2	14771-ZE1-T01	4544284
11	PLATE, PUSH ROD GUIDE	a	b	c	d	-------	-------	1	14791-ZE0-010	1929769
12	BOLT, PIVOT	a	b	c	d	-------	-------	2	90012-ZE0-010	1756964
13	NUT, PIVOT ADJUSTING	a	b	c	d	-------	-------	2	90206-ZE1-000	1431287
14	PIN, WEIGHT CENTER	a	b	c	d	-------	-------	1	90701-ZG9-800	4327557
15	COLLAR, WEIGHT CENTER	a	b	c	d	-------	-------	1	91502-ZG9-800	4452355

CARBURETOR



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GXV140

BLOCK NO. E-14

Ref. No.	DESCRIPTION	TYPE A1	TYPE A2	TYPE N1	TYPE N2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
		a	b	c	d					
1	GASKET SET	a	b	c	d	-------	-------	1	16010-ZG9-800	4428827
2	VALVE SET, FLOAT	a	b	c	d	-------	-------	1	16011-ZE0-005	1441476
3	FLOAT SET	a	b	c	d	-------	-------	1	16013-ZE0-005	1441492
4	CHAMBER SET, FLOAT	a	b	c	d	-------	-------	1	16015-ZG9-800	4428835
5	SCREW SET	a	b	c	d	-------	-------	1	16016-ZH7-W01	4219879
6	SCREW SET B	a	b	c	d	-------	-------	1	16028-ZE0-005	1441518
7	CHOKE SET	a	b	c	d	-------	-------	1	16045-ZE7-005	3352671
8	CARBURETOR ASSY. (BE53A A)	a	b	c	d	-------	-------	1	16100-ZG9-800	4428843
9	SCREW, THROTTLE STOP	a	b	c	d	-------	-------	1	16124-ZE0-005	1441559
10	NOZZLE, MAIN	a	b	c	d	-------	-------	1	16166-ZG9-800	4428850
11	INSULATOR, CARBURETOR	a	b	c	d	-------	-------	1	16211-ZG9-000	3307311
12	PACKING, CARBURETOR (HPE)	a	b	c	d	-------	-------	1	16212-ZG9-T00	4224267
13	SPACER COMP., CARBURETOR	a	b	c	d	-------	-------	1	16220-ZE6-010	2455640
14	GASKET, CARBURETOR	a	b	c	d	-------	-------	1	16221-ZG9-T00	4224275
15	LEVER, VALVE	a	b	c	d	-------	-------	1	16953-ZE6-005	2580116
16	PLATE, LEVER SETTING	a	b	c	d	-------	-------	1	16954-ZE1-811	1807791

General Purpose Engine
G100 • G100K1 • G100K2

HONDA
Power
Equipment

Parts Catalog

Second Edition

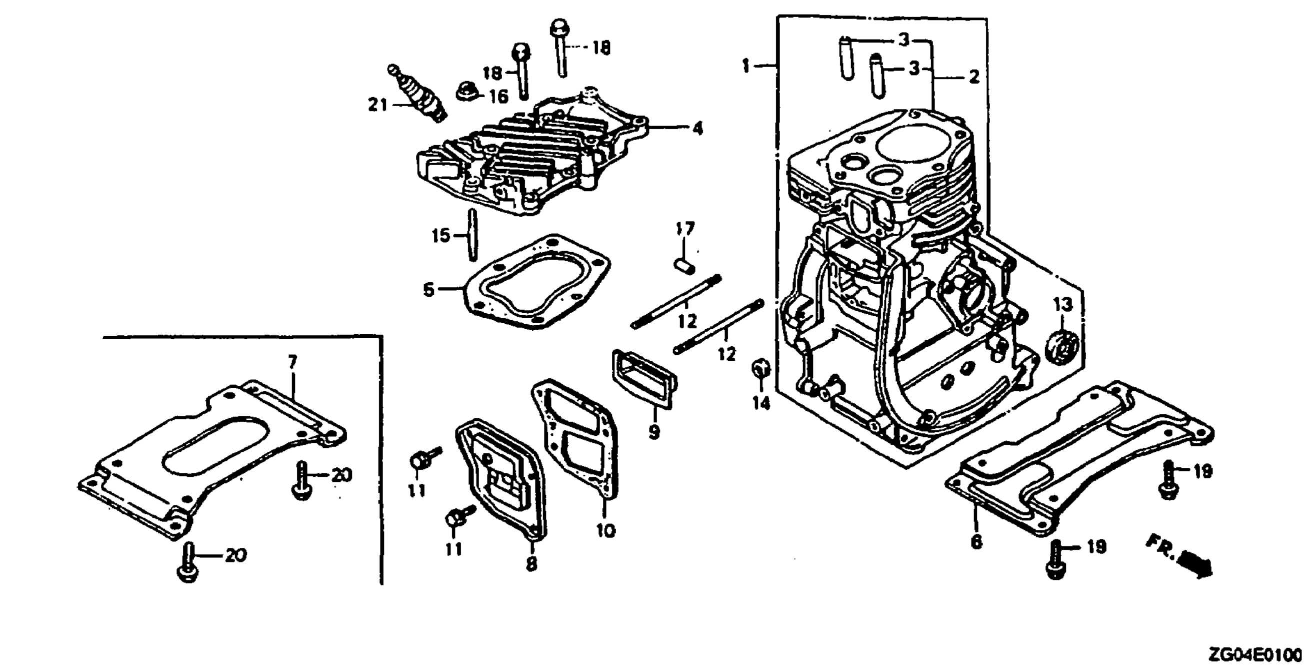
July, 1996

AMERICAN HONDA MOTOR CO., INC.

14ZG00E2-AH

PRINTED IN USA

CYLINDER BARREL



G100
G100K1
G100K2

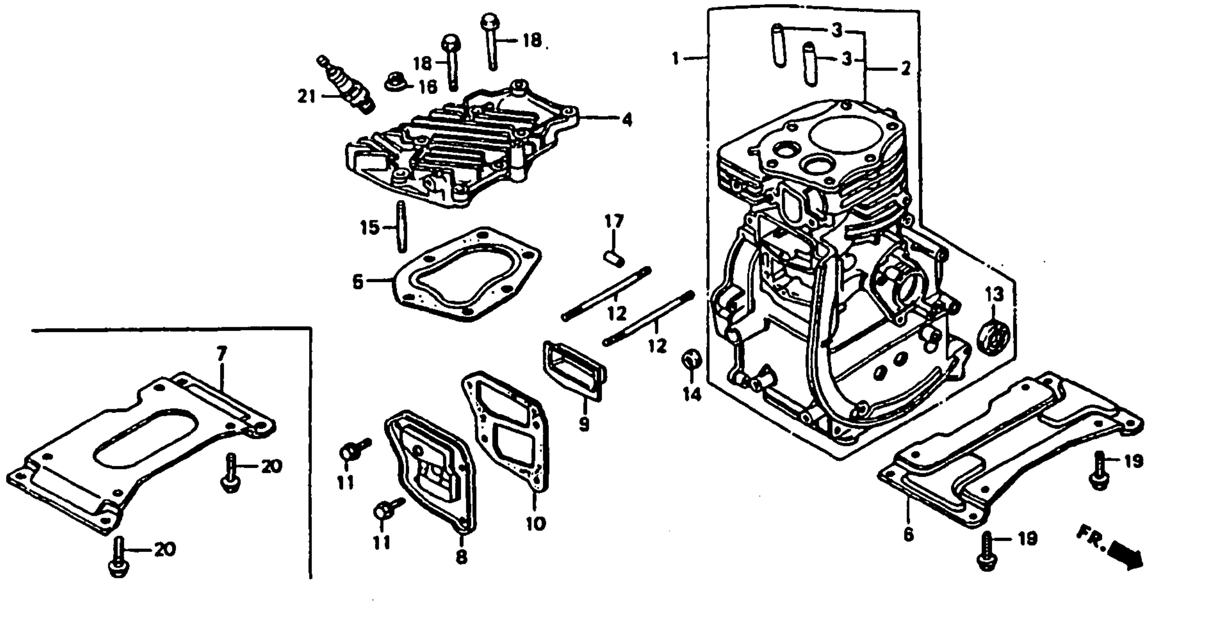
BLOCK NO. E-1

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
1	CYLINDER ASSY.	●				●	●			-------	2143546	1	120A0-ZG0-000	1794924
			●		●					-------	2143546	1	120A0-ZG0-000	1794924
				●				●		-------	2143546	1	120A0-ZG0-000	1794924
	CYLINDER ASSY.	●				●	●			-------	-------	1	120A0-ZG0-010	3210846
			●		●					-------	-------	1	120A0-ZG0-010	3210846
				●				●		-------	-------	1	120A0-ZG0-010	3210846
	CYLINDER ASSY.			●	●			●	●	-------	-------	1	12000-ZG0-020	4481362
2	CYLINDER COMP.	●					●			-------	1010983	1	12100-896-305	0927368
	CYLINDER COMP.	●				●	●			-------	-------	1	12100-896-315	1033026
3	GUIDE, VALVE (OS)	●				●	●			-------	-------	(2)	12133-896-306	4457842
			●		●					2376620	-------	(2)	12133-896-306	4457842
			●		●					-------	2376619	(2)	12133-896-306	4457842
				●	●			●	●	-------	-------	(2)	12133-896-306	4457842
	GUIDE, VALVE	●				●	●			-------	-------	(2)	12134-896-305	0927376
			●		●					-------	2376619	(2)	12134-896-305	0927376
4	CYLINDER HEAD	●				●	●			-------	-------	1	12221-896-000	0927384
	CYLINDER HEAD		●		●					-------	2422128	1	12221-ZG0-000	1794932
	CYLINDER HEAD		●		●					2422129	-------	1	12221-ZG0-010	4481404

G100
G100K1
G100K2

Ref. No.	BLOCK NO. E-1 DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
4	CYLINDER HEAD		●		●					2422129	-------	1	12221-ZG0-020	4640413
				●	●			●		-------	3058813	1	12221-ZG0-020	4640413
				●				●		-------	3058813	1	12221-ZG0-020	4640413
	CYLINDER HEAD			●	●			●		3058814	-------	1	12221-ZG0-030	4776001
				●				●		3058814	-------	1	12221-ZG0-030	4776001
				●					●	-------	-------	1	12221-ZG0-030	4776001
5	GASKET, CYLINDER HEAD	●				●	●			-------	-------	1	12281-896-000	0927392
	GASKET, CYLINDER HEAD	●				●	●			-------	-------	1	12281-896-306	4192910
	GASKET, CYLINDER HEAD		●		●					-------	-------	1	12281-ZG0-003	2084838
	GASKET, CYLINDER HEAD			●	●			●	●	-------	-------	1	12281-ZC0-003	2064723
6	BED, ENGINE (Q-TYPE)	●				●	●			1443596	-------	1	12351-ZG0-810	1794965
			●		●					-------	-------	1	12351-ZG0-810	1794965
				●	●			●		-------	-------	1	12351-ZG0-810	1794965
	BED, ENGINE (STD.)			●					●	-------	-------	1	12351-ZG0-000	5176177
7	BED, ENGINE	●				●	●			-------	1443595	1	12351-896-630	0927400
8	COVER, TAPPET	●				●	●			-------	-------	1	12361-896-000	0927418
	COVER, TAPPET ROOM		●		●					-------	-------	1	12361-ZG0-000	1794973
				●	●			●	●	-------	-------	1	12361-ZG0-000	1794973
9	SEPARATOR (INNER)	●					●			-------	1014735	1	12365-896-000	0927426
	SEPARATOR COMP. (INNER)	●					●			-------	1014735	1	12365-896-700	0933291
	SEPARATOR COMP. (INNER)	●				●	●			-------	-------	1	12370-896-000	0942730
	SEPARATOR COMP. (INNER)		●		●					-------	-------	1	12370-ZG0-000	1794981
				●	●			●	●	-------	-------	1	12370-ZG0-000	1794981
10	GASKET, TAPPET COVER	●				●	●			-------	-------	1	12375-896-000	0927434
	GASKET, TAPPET COVER		●		●					-------	2410563	1	12375-ZG0-000	1794999
	GASKET, TAPPET COVER		●		●					-------	-------	1	12375-ZG0-010	4454534
				●	●			●	●	-------	-------	1	12375-ZG0-010	4454534
11	BOLT, FLANGE (5X10)	●				●	●			-------	-------	4	90002-892-000	0928051
			●		●					-------	-------	4	90002-892-000	0928051
				●	●			●	●	-------	-------	4	90002-892-000	0928051
12	BOLT, STUD (5X80)	●				●	●			-------	-------	2	90041-896-000	0928085
			●		●					-------	-------	2	90041-896-000	0928085
				●	●			●	●	-------	-------	2	90041-896-000	0928085
13	OIL SEAL (17X30X6) (NOK)	●				●	●			-------	-------	1	91202-892-004	0866145
			●		●					-------	-------	1	91202-892-004	0866145
				●	●			●	●	-------	-------	1	91202-892-004	0866145
	OIL SEAL (17X30X6) (ARAI)		●		●					-------	-------	1	91202-892-003	1104884

CYLINDER BARREL



ZG04E0100

G100
G100K1
G100K2

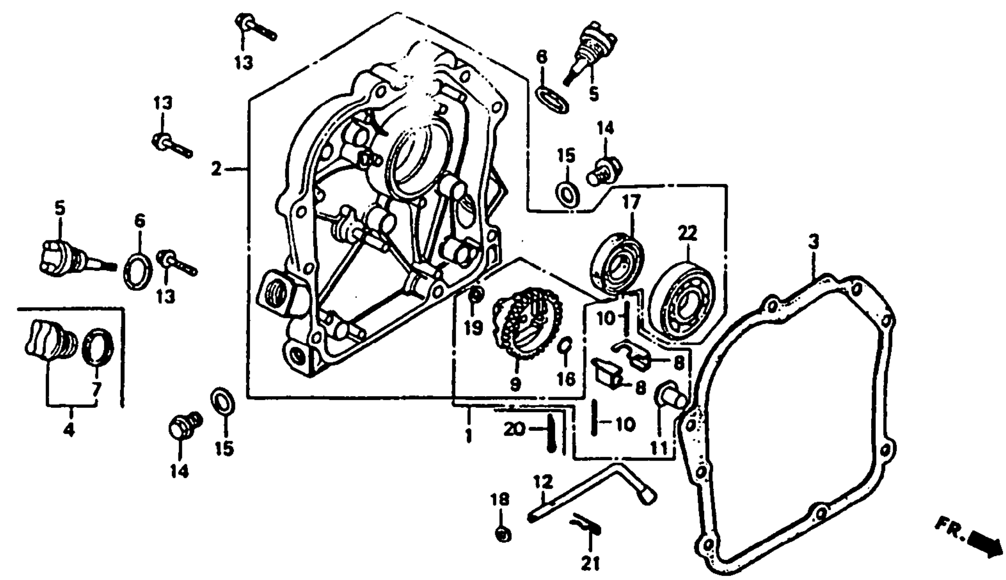
BLOCK NO. E-1

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
14	OIL SEAL	●				●	●			-------	-------	1	91231-816-000	0158998
			●		●					-------	-------	1	91231-816-000	0158998
				●	●			●	●	-------	-------	1	91231-816-000	0158998
15	BOLT, STUD (6X45)	●				●	●			-------	-------	2	92700-06045-3B	0928119
	BOLT, STUD (6X45)	●				●	●			-------	-------	2	92900-06028-3B	4932208
16	NUT, FLANGE (6MM)	●				●	●			-------	-------	2	94050-06080	0612689
17	PIN A, DOWEL (8X14)	●				●	●			-------	-------	2	94301-08140	0069310
			●		●					-------	-------	2	94301-08140	0069310
				●	●			●	●	-------	-------	2	94301-08140	0069310
18	BOLT, FLANGE (6X35)	●					●			-------	1001095	4	95700-06035-08	0498238
	BOLT, FLANGE (6X35)	●					●			-------	1001095	4	95701-06035-08	2170801
	BOLT, FLANGE (6X35)	●				●				-------	-------	4	95718-06035-08	1405232
		●					●			1001096	-------	4	95718-06035-08	1405232
	BOLT, FLANGE (6X35)		●		●					-------	-------	6	95801-06035-00	2569069
				●	●			●	●	-------	-------	6	95801-06035-00	2569069
	BOLT, FLANGE (6X35)		●		●					-------	-------	6	95818-06035-00	1825124
				●	●			●	●	-------	-------	6	95818-06035-00	1825124
19	BOLT, FLANGE (8X18)		●		●					-------	-------	4	95700-08018-00	1096791

G100
G100K1
G100K2

Ref. No.	DESCRIPTION (BLOCK NO. E-1)	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
19	BOLT, FLANGE (8X18)		●		●					------	------	4	95701-08018-00	2660694
				●	●			●	●	------	------	4	95701-08018-00	2660694
20	BOLT, FLANGE (8X18)	●				●	●			------	------	4	95700-08018-08	0928150
	BOLT, FLANGE (8X18)	●				●	●			------	------	4	95701-08018-08	2563237
21	SPARK PLUG (BM-4A) (NGK)	●				●	●			------	------	1	98073-54740	0928168
	SPARK PLUG (BMR-4A) (NGK)	●				●	●			------	------	(1)	98073-54744	0940759
			●		●					------	------	1	98073-54744	0940759
	SPARK PLUG (W14M-U) (ND)	●				●	●			------	------	(1)	98073-54750	1420603
	SPARK PLUG (W14MR-U) (ND)	●				●	●			------	------	(1)	98073-54754	1668896
			●		●					------	------	1	98073-54754	1668896
	SPARK PLUG (BPM4A-10) (NGK)	●				●	●			------	------	(1)	98073-54941	1033539
	SPARK PLUG (BPMR-4A10)	●				●	●			------	------	(1)	98073-54944	1202498
	SPARK PLUG (W14MP-U10) (ND)	●				●	●			------	------	(1)	98073-54951	1842467
	SPARK PLUG (BRMR4A)			●	●			●	●	------	------	1	98073-54776	4497996

CRANKCASE COVER



G100
G100K1
G100K2

BLOCK NO. E-2

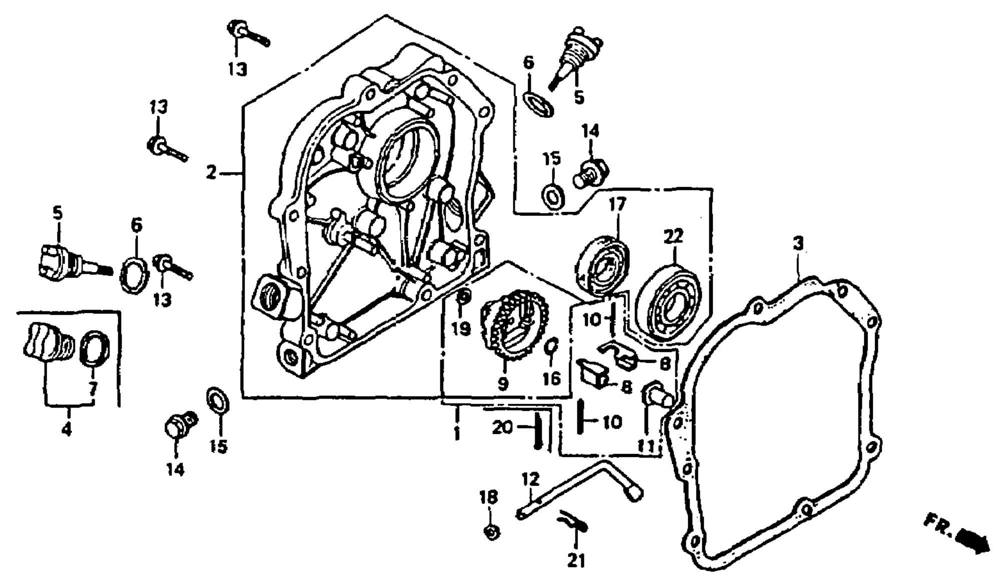
Ref. No.	DESCRIPTION	G100	G100K1	G100K2	QA	QAF	QAH	QAD2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	GOVERNOR KIT (STD)		●		●					-------	-------	(1)	06165-Z60-000	3313624
				●	●			●	●	-------	-------	(1)	06165-Z60-000	3313624
2	COVER ASSY., CRANKCASE	●				●	●			-------	-------	1	11300-896-000	0927343
	COVER ASSY., CRANKCASE		●		●					-------	-------	1	11300-Z60-000	1840370
				●	●			●		-------	-------	1	11300-Z60-000	1840370
	COVER ASSY., CRANKCASE			●					●	-------	-------	1	11300-Z60-010	5176110
3	GASKET, CASE COVER	●				●	●			-------	-------	1	11381-896-000	0927350
	GASKET, CASE COVER		●		●					-------	2400550	1	11381-Z60-000	1794916
	GASKET, CASE COVER		●		●					-------	2400550	1	11381-Z60-306	4437760
	GASKET, CASE COVER		●		●					-------	-------	1	11381-Z60-800	4034971
				●	●			●	●	-------	-------	1	11381-Z60-800	4034971
4	CAP ASSY., OIL FILLER			●	●			●	●	-------	-------	1	15600-Z64-003	4497921
5	CAP, OIL FILLER	●				●	●			-------	-------	2	15620-896-000	0927541
	CAP, OIL FILLER		●		●					-------	-------	2	15620-Z60-010	1814326
				●	●			●		-------	3126184	1	15620-Z60-010	1814326
	CAP, OIL FILLER			●	●			●		3126185	-------	1	15620-Z60-003	5164207
				●					●	-------	-------	1	15620-Z60-003	5164207

G100
G100K1
G100K2

BLOCK NO. E-2

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
6	GASKET, OIL FILLER CAP	●					●			-------	1061541	2	15621-896-000	0927558
	GASKET, OIL FILLER CAP	●				●	●			-------	-------	2	15621-896-010	1033042
	GASKET, OIL FILLER CAP		●		●					-------	-------	2	15625-ZG0-000	1795103
				●	●			●	●	-------	-------	1	15625-ZG0-000	1795103
7	GASKET, OIL FILLER CAP			●	●			●	●	-------	-------	1	15625-ZE1-003	4497947
8	WEIGHT, GOVERNOR	●				●	●			-------	-------	2	16511-896-000	0927632
			●		●					-------	-------	2	16511-896-000	0927632
				●	●			●	●	-------	-------	2	16511-896-000	0927632
9	HOLDER, GOVERNOR WEIGHT	●				●	●			1443596	-------	1	16512-ZG0-000	1795160
			●		●					-------	-------	1	16512-ZG0-000	1795160
				●	●			●	●	-------	-------	1	16512-ZG0-000	1795160
	HOLDER, GOVERNOR WEIGHT	●				●	●			-------	1443595	1	16512-896-300	0927640
10	PIN, GOVERNOR WEIGHT	●				●	●			1443596	-------	2	16513-ZE1-000	1427244
			●		●					-------	-------	2	16513-ZE1-000	1427244
				●	●			●	●	-------	-------	2	16513-ZE1-000	1427244
11	SLIDER, GOVERNOR	●				●	●			1443596	-------	1	16531-ZG0-000	1795178
			●		●					-------	-------	1	16531-ZG0-000	1795178
				●	●			●	●	-------	-------	1	16531-ZG0-000	1795178
	SLIDER, GOVERNOR	●				●	●			-------	1443595	1	16531-896-000	0927657
12	SHAFT, GOVERNOR ARM	●				●	●			-------	-------	1	16541-896-000	0927665
			●		●					-------	-------	1	16541-896-000	0927665
				●	●			●	●	-------	-------	1	16541-896-000	0927665
13	BOLT, FLANGE (6X28)	●				●	●			-------	-------	6	95700-06028-08	0252296
	BOLT, FLANGE (6X28)	●				●	●			-------	-------	6	95701-06028-08	2488500
	BOLT, FLANGE (6X28)		●		●					-------	-------	6	90015-883-000	0636852
				●	●			●	●	-------	-------	6	90015-883-000	0636852
14	BOLT, DRAIN PLUG	●				●	●			-------	-------	2	90131-883-000	0636902
	BOLT, DRAIN PLUG	●				●	●			-------	-------	2	90131-896-650	1986231
	BOLT, DRAIN PLUG		●		●					-------	-------	2	90131-ZE1-000	1431246
				●	●			●	●	-------	-------	2	90131-ZE1-000	1431246
15	WASHER, DRAIN PLUG (12MM)	●				●	●			-------	-------	2	94109-12000	0171868
	WASHER, DRAIN PLUG (10.2MM)		●		●					-------	-------	2	90601-ZE1-000	1436583
				●	●			●	●	-------	-------	2	90601-ZE1-000	1436583
16	CLIP, GOVERNOR HOLDER	●				●	●			2198807	-------	1	90602-ZE1-000	2456697
		●				●	●			-------	-------	1	90602-ZE1-000	2456697
			●		●					-------	-------	1	90602-ZE1-000	2456697
				●	●			●	●	-------	-------	1	90602-ZE1-000	2456697
				●				●		-------	2198806	1	90602-ZE1-000	2456697

CRANKCASE COVER



ZG04E0200B

G100
G100K1
G100K2

BLOCK NO. E-2

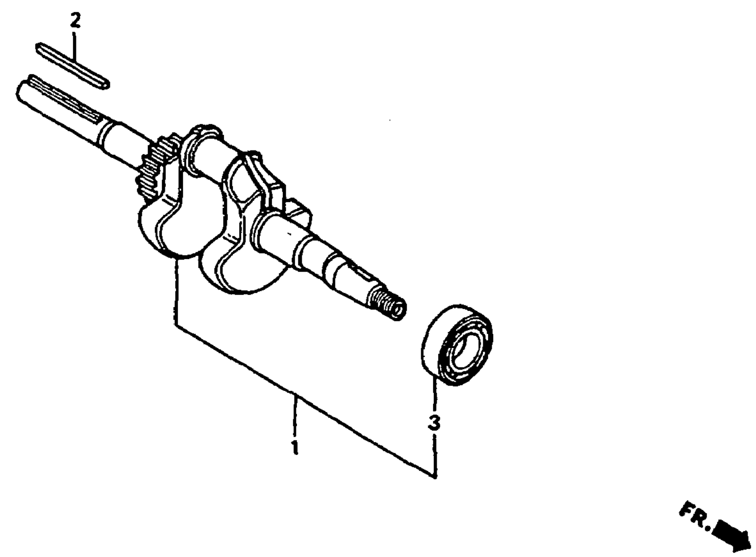
Ref. No.	DESCRIPTION	G100	G100K1	G100K2	TYPE: CA	TYPE: QAF	TYPE: QAH	TYPE: QA2	TYPE: SMD2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
16	CLIP, GOVERNOR HOLDER	●				●	●			-------	-------	1	90602-896-000	0928101
			●		●					-------	2198806	1	90602-896-000	0928101
				●				●		-------	2198806	1	90602-896-000	0928101
17	OIL SEAL (17X30X6) (NOK)	●				●	●			-------	-------	1	91202-892-004	0866145
			●		●					-------	-------	1	91202-892-004	0866145
				●	●			●	●	-------	-------	1	91202-892-004	0866145
	OIL SEAL (17X30X6) (ARAI)		●		●					-------	-------	1	91202-892-003	1104884
18	WASHER, PLAIN (5MM)	●				●	●			-------	-------	1	94101-05800	0285791
	WASHER, PLAIN (5MM)		●		●					-------	-------	1	94101-05000	0059055
				●	●			●	●	-------	-------	1	94101-05000	0059055
19	WASHER, PLAIN (6MM)	●				●	●			-------	-------	1	94101-06800	0345900
			●		●					-------	-------	1	94101-06800	0345900
				●	●			●	●	-------	-------	1	94101-06800	0345900
	WASHER, PLAIN (6MM)		●		●					-------	-------	1	94101-06000	0059071
				●	●			●	●	-------	-------	1	94101-06000	0059071
	WASHER, PLAIN (6MM)		●		●					-------	-------	1	94101-06080	3136074
				●	●			●	●	-------	-------	1	94101-06080	3136074
20	PIN, COTTER (2.5X28)	●				●	●			-------	1443595	2	94201-25280	0928135

G100
G100K1
G100K2

BLOCK NO. E-2

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
21	PIN, LOCK (8MM)	●				●	●			--------	--------	1	94251-08000	0115527
			●		●					--------	--------	1	94251-08000	0115527
				●	●			●	●	--------	--------	1	94251-08000	0115527
22	BEARING, RADIAL BALL (6203)	●				●	●			--------	--------	1	96100-62030-00	0722199
			●		●					--------	--------	1	96100-62030-00	0722199
				●	●			●	●	--------	--------	1	96100-62030-00	0722199

CRANKSHAFT

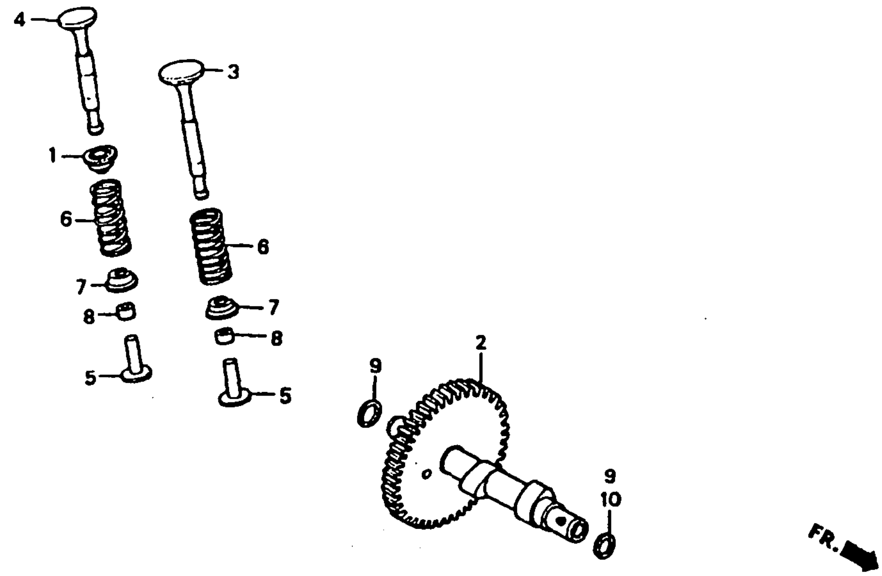


ZG04E0500A

G100
G100K1
G100K2

Ref. No.	BLOCK NO. E-5 DESCRIPTION	G100	G100K1	G100K2	TYPE QA	TYPE QAF	TYPE QAH	TYPE QA2	TYPE SMD2	ENGINE SERIAL NUMBER FROM	ENGINE SERIAL NUMBER TO	QTY REQ	PART NUMBER	HONDA CODE
1	CRANKSHAFT COMP. (Q-TYPE)	●				●	●			-------	2207846	1	13310-ZG0-600	1795020
			●		●					-------	2207846	1	13310-ZG0-600	1795020
				●				●		-------	2207846	1	13310-ZG0-600	1795020
	CRANKSHAFT COMP. (Q-TYPE)	●				●	●			-------	-------	1	13310-ZG0-601	3499704
			●		●					-------	-------	1	13310-ZG0-601	3499704
				●				●		-------	2207846	1	13310-ZG0-601	3499704
				●	●			●		-------	-------	1	13310-ZG0-601	3499704
	CRANKSHAFT COMP.	●				●	●			-------	-------	1	13310-896-630	0927483
	CRANKSHAFT COMP. (S-TYPE)			●					●	-------	-------	1	13310-ZG0-010	5176185
2	KEY (4.78X4.78X38)		●		●					-------	-------	1	90745-ZE1-600	1441062
				●	●			●		-------	-------	1	90745-ZE1-600	1441062
3	BEARING, RADIAL BALL (6203)	●				●	●			-------	-------	1	96100-62030-00	0722199
			●		●					-------	-------	1	96100-62030-00	0722199
				●	●			●	●	-------	-------	1	96100-62030-00	0722199

CAMSHAFT



ZG04E0600A

G100
G100K1
G100K2

BLOCK NO. E-6

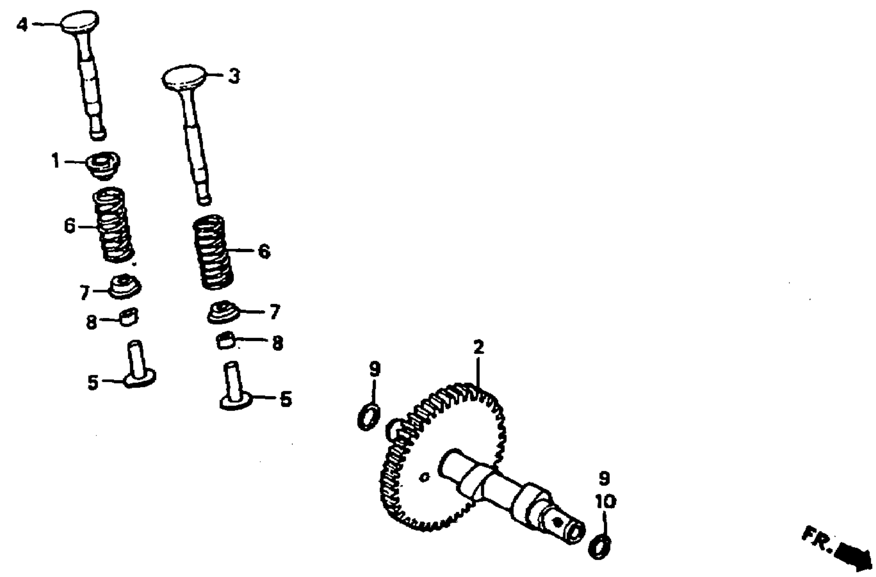
NO.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	SEAL, VALVE STEM			●				●	●	-------	-------	1	12209-Z61-H11	2821528
2	CAMSHAFT COMP.	●					●			-------	1063118	1	14111-896-000	0927491
	CAMSHAFT COMP.	●				●	●			-------	-------	1	14111-896-010	1068337
	CAMSHAFT COMP.		●		●					2346140	-------	1	14111-ZC0-000	2064830
				●	●			●	●	-------	-------	1	14111-ZC0-000	2064830
	CAMSHAFT COMP.		●		●					-------	2346139	1	14111-Z60-000	1795038
3	VALVE, IN.	●				●	●			-------	-------	1	14711-896-000	0927517
	VALVE, IN.		●		●					-------	-------	1	14711-ZG0-000	1795053
	VALVE, IN.			●	●			●	●	-------	-------	1	14711-ZG1-H10	2821536
	VALVE, IN.			●	●					-------	-------	1	14711-ZG1-000	1817105
4	VALVE, EX.	●				●	●			-------	-------	1	14721-896-000	0927525
	VALVE, EX.		●		●					-------	-------	1	14721-ZG0-000	1795061
	VALVE, EX.			●	●			●	●	-------	-------	1	14721-ZG1-H10	2821544
	VALVE, EX.			●	●			●	●	-------	-------	1	14721-Z61-000	1817113
5	LIFTER, VALVE	●					●			-------	1085262	2	14732-892-000	0865048
	LIFTER, VALVE	●				●	●			-------	-------	2	14732-892-010	1068345

G100
G100K1
G100K2

BLOCK NO. E-6

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
5	LIFTER, VALVE		●		●					------	------	2	14732-ZC0-000	2271278
				●	●			●	●	------	------	2	14732-ZC0-000	2271278
	LIFTER, VALVE		●		●					------	2063201	2	14732-ZG0-000	1795079
6	SPRING, VALVE	●				●	●			------	------	2	14751-896-000	0927533
			●		●					------	------	2	14751-896-000	0927533
				●	●			●	●	------	------	2	14751-896-000	0927533
7	RETAINER, VALVE SPRING	●				●	●			1443596	------	2	14771-ZG0-000	1795087
			●		●					------	------	2	14771-ZG0-000	1795087
				●	●			●	●	------	------	2	14771-ZG0-000	1795087
	RETAINER, VALVE SPRING	●				●	●			------	1443595	2	14771-892-000	0865063
8	ADJUSTER, TAPPET CLEARANCE (3.15)	●				●	●			------	------	2	14801-892-000	0866160
			●		●					------	------	2	14801-892-000	0866160
				●	●			●	●	------	------	2	14801-892-000	0866160
	ADJUSTER, TAPPET CLEARANCE (3.25)	●				●	●			------	------	2	14803-892-000	0866178
			●		●					------	------	2	14803-892-000	0866178
				●	●			●	●	------	------	2	14803-892-000	0866178
	ADJUSTER, TAPPET CLEARANCE (3.34)	●				●	●			------	------	2	14806-892-000	0866186
			●		●					------	------	2	14806-892-000	0866186
				●	●			●	●	------	------	2	14806-892-000	0866186
	ADJUSTER, TAPPET CLEARANCE (3.43)	●				●	●			------	------	2	14809-892-000	0866194
			●		●					------	------	2	14809-892-000	0866194
				●	●			●	●	------	------	2	14809-892-000	0866194
	ADJUSTER, TAPPET CLEARANCE (3.52)	●				●	●			------	------	2	14812-892-000	0866202
			●		●					------	------	2	14812-892-000	0866202
				●	●			●	●	------	------	2	14812-892-000	0866202
	ADJUSTER, TAPPET CLEARANCE (3.61)	●				●	●			------	------	2	14815-892-000	0866210
			●		●					------	------	2	14815-892-000	0866210
				●	●			●	●	------	------	2	14815-892-000	0866210
	ADJUSTER, TAPPET CLEARANCE (3.72)	●				●	●			------	------	2	14818-892-000	0866228
			●		●					------	------	2	14818-892-000	0866228
				●	●			●	●	------	------	2	14818-892-000	0866228
	ADJUSTER, TAPPET CLEARANCE (3.82)	●				●	●			------	------	2	14820-892-000	0866236
			●		●					------	------	2	14820-892-000	0866236
				●	●			●	●	------	------	2	14820-892-000	0866236
9	WASHER (10MM)	●				●				------	------	1	90412-329-000	0279620
		●					●			1000944	1033288	2	90412-329-000	0279620
		●					●			1033289	------	1	90412-329-000	0279620
	WASHER, THRUST (9.9MM)	●					●			------	1000943	2	90452-892-000	0866129
	WASHER (12MM)		●		●					------	------	2	90452-ZG0-000	1795756
				●	●			●	●	------	------	2	90452-ZG0-000	1795756

CAMSHAFT

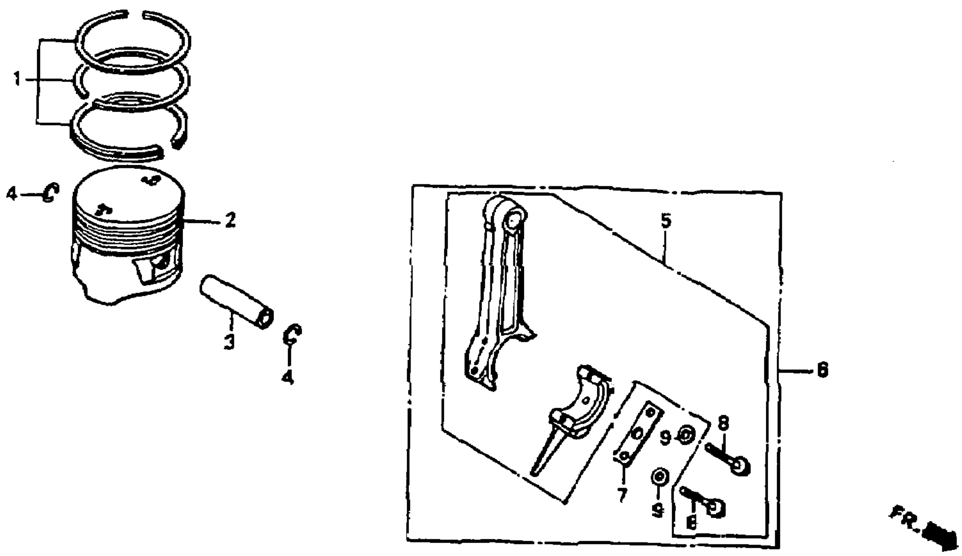


G100
G100K1
G100K2

BLOCK NO. E-6

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
10	WASHER, THRUST (9.9MM)	●				●				-------	-------	1	90452-892-000	0866129
		●					●			1033289	-------	1	90452-892-000	0866129

PISTON • CONNECTING ROD

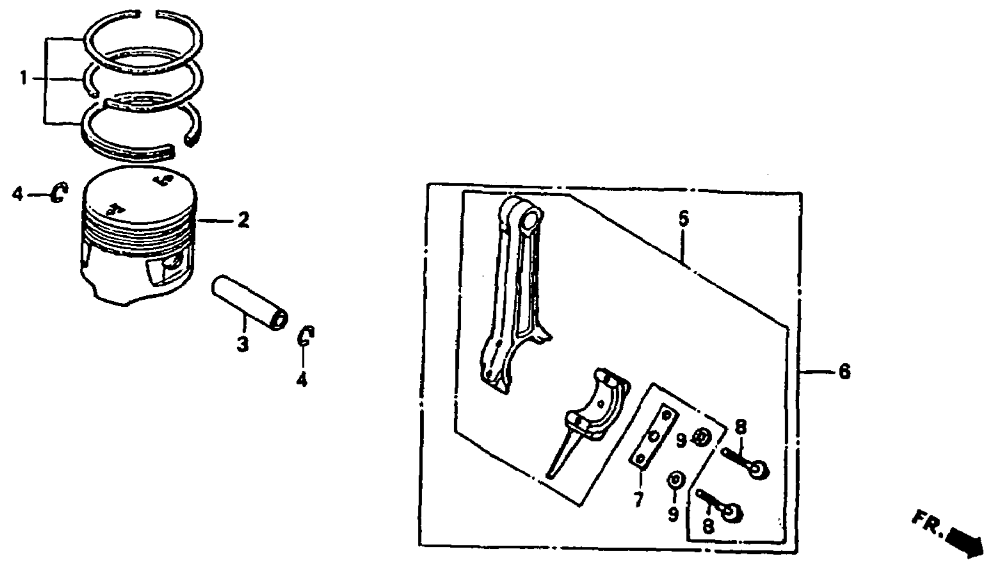


ZG04E0700

G100
G100K1
G100K2

Ref. No.	BLOCK NO. E-7 DESCRIPTION	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	RING SET, PISTON (STD)	●				●	●			------	------	1	130A1-896-003	1104595
	RING SET, PISTON (STD)	●				●	●			------	------	1	130A1-896-004	1410257
	RING SET, PISTON (0.25)	●				●	●			------	------	(1)	130B1-896-003	1104603
	RING SET, PISTON (0.25)	●				●	●			------	------	(1)	130B1-896-004	1410265
	RING SET, PISTON (0.50)	●				●	●			------	------	(1)	130C1-896-003	1104611
	RING SET, PISTON (0.50)	●				●	●			------	------	(1)	130C1-896-004	1410273
	RING SET, PISTON (0.75)	●				●	●			------	------	(1)	130D1-896-003	1104629
	RING SET, PISTON (0.75)	●				●	●			------	------	(1)	130D1-896-004	1410281
	RING SET, PISTON (STD)	●					●			------	------	1	13010-896-003	1007384
	RING SET, PISTON (0.25)	●					●			------	------	(1)	13011-892-003	0876805
	RING SET, PISTON (0.25)	●					●			------	------	(1)	13011-896-003	0965624
	RING SET, PISTON (0.50)	●					●			------	------	(1)	13012-892-003	0876813
	RING SET, PISTON (0.50)	●					●			------	------	(1)	13012-896-003	0965632
	RING SET, PISTON (0.75)	●					●			------	------	(1)	13013-892-003	0876821
	RING SET, PISTON (0.75)	●					●			------	------	(1)	13013-896-003	0965640
	RING SET, PISTON (STD)		●		●					------	------	1	13010-ZG0-003	1796010

PISTON • CONNECTING ROD



ZG04E0700

G100
G100K1
G100K2

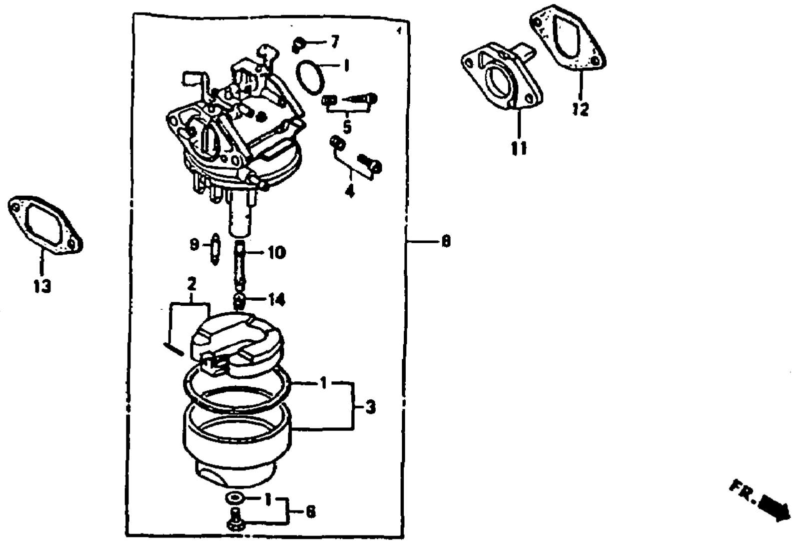
Ref. No.	BLOCK NO. E-7 DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	RING SET, PISTON (STD)		●		●					-------	-------	1	13010-ZG0-004	1796028
	RING SET, PISTON (0.25)		●		●					-------	-------	(1)	13011-ZG0-003	1796036
	RING SET, PISTON (0.25)		●		●					-------	-------	(1)	13011-ZG0-004	1796044
	RING SET, PISTON (0.50)		●		●					-------	-------	(1)	13012-ZG0-003	1796051
	RING SET, PISTON (0.50)		●		●					-------	-------	(1)	13012-ZG0-004	1796069
	RING SET, PISTON (0.75)		●		●					-------	-------	(1)	13013-ZG0-003	1796077
	RING SET, PISTON (0.75)		●		●					-------	-------	(1)	13013-ZG0-004	1796085
	RING SET, PISTON (STD)			●	●			●	●	-------	-------	1	13010-ZC0-003	2064731
	RING SET, PISTON (0.25)			●	●			●	●	-------	-------	(1)	13011-ZC0-003	2064749
	RING SET, PISTON (0.50)			●	●			●	●	-------	-------	(1)	13012-ZC0-003	2064756
	RING SET, PISTON (0.75)			●	●			●	●	-------	-------	(1)	13013-ZC0-003	2064764
2	PISTON	●				●	●			-------	-------	1	13101-ZA8-000	1787381
	PISTON (STD)	●				●	●			-------	-------	1	13101-892-000	0864959
	PISTON (0.25)	●				●	●			-------	-------	(1)	13102-ZA8-000	1819234
	PISTON (0.25)	●				●	●			-------	-------	(1)	13102-892-000	0876839
	PISTON (0.50)	●				●	●			-------	-------	(1)	13103-ZA8-000	1819259

G100
G100K1
G100K2

BLOCK NO. E-7

Ref. No.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
2	PISTON (0.50)	●				●	●			-------	-------	(1)	13103-892-000	0876847
	PISTON (0.75)	●				●	●			-------	-------	(1)	13104-ZA8-000	1819275
	PISTON (0.75)	●				●	●			-------	-------	(1)	13104-892-000	0876854
	PISTON (STD)		●		●					-------	-------	1	13101-ZG0-003	1795004
	PISTON (0.25)		●		●					-------	-------	(1)	13102-ZG0-003	1796093
	PISTON (0.50)		●		●					-------	-------	(1)	13103-ZG0-003	1796101
	PISTON (0.75)		●		●					-------	-------	(1)	13104-ZG0-003	1796119
	PISTON (STD)			●	●			●	●	-------	-------	1	13101-ZC0-003	2064772
	PISTON (0.25)			●	●			●	●	-------	-------	(1)	13102-ZC0-003	2064780
	PISTON (0.50)			●	●			●	●	-------	-------	(1)	13103-ZC0-003	2064798
	PISTON (0.75)			●	●			●	●	-------	-------	(1)	13104-ZC0-003	2064806
3	PIN, PISTON	●				●	●			-------	-------	1	13111-892-000	0864967
			●		●					-------	-------	1	13111-892-000	0864967
				●	●			●	●	-------	-------	1	13111-892-000	0864967
4	CLIP, PISTON PIN (10MM)	●				●	●			-------	-------	2	13115-147-000	0463380
			●		●					-------	-------	2	13115-147-000	0463380
				●	●			●	●	-------	-------	2	13115-147-000	0463380
5	ROD ASSY., CONNECTING (STD)	●				●	●			1443596	-------	1	13200-ZG0-000	1795012
			●		●					-------	-------	1	13200-ZG0-000	1795012
				●	●			●	●	-------	-------	1	13200-ZG0-000	1795012
	ROD ASSY., CONNECTING (UNDER SIZE)	●				●	●			1443596	-------	(1)	13200-ZG0-305	1796127
			●		●					-------	-------	(1)	13200-ZG0-305	1796127
				●	●			●	●	-------	-------	(1)	13200-ZG0-305	1796127
6	ROD ASSY., CONNECTING	●				●	●			-------	1443595	1	13200-892-000	0864975
	ROD ASSY., CONNECTING (U.S. 0.25)	●				●	●			-------	1443595	(1)	13200-892-305	0933317
7	WASHER, CONNECTING ROD	●				●	●			-------	1443595	1	13213-892-000	0864983
8	BOLT, CONNECTING ROD	●				●	●			1443596	-------	2	90001-ZG0-000	1795707
			●		●					-------	-------	2	90001-ZG0-000	1795707
				●	●			●	●	-------	-------	2	90001-ZG0-000	1795707
	BOLT, CONNECTING ROD	●				●	●			-------	1443595	2	90001-892-003	0947390
9	WASHER, LOCK	●				●	●			-------	1443595	2	90456-892-000	0866137

G100 - CARBURETOR



ZG04E1100

G100
G100K1
G100K2

BLOCK NO. E-11

ef. o.	DESCRIPTION	G100	G100K1	G100K2	TYPE QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
1	GASKET SET	●				●	●			-------	-------	1	16010-896-005	0927574
	GASKET SET	●				●	●			-------	-------	1	16010-896-015	4554838
2	FLOAT SET	●				●	●			-------	-------	1	16013-883-005	0636258
3	CHAMBER SET, FLOAT	●				●	●			-------	-------	1	16015-891-003	3476744
	CHAMBER SET, FLOAT	●				●	●			-------	-------	1	16015-896-701	2473312
4	SCREW SET A	●				●	●			-------	-------	1	16016-892-005	0897645
5	SCREW SET A	●				●	●			-------	-------	1	16016-896-005	1033075
6	SCREW SET B	●				●	●			-------	-------	1	16028-ZE0-005	1441518
	SCREW SET B	●				●	●			-------	-------	1	16028-883-005	0636274
7	SCREW, PLUG	●				●	●			-------	-------	1	16071-881-003	0927582
8	CARBURETOR ASSY.	●				●	●			-------	-------	1	16100-896-308	4424982
	CARBURETOR ASSY.	●				●	●			-------	-------	1	16100-896-661	1033083
9	VALVE COMP., FLOAT	●				●	●			-------	-------	1	16155-883-005	0636282
10	NOZZLE, MAIN	●				●	●			-------	-------	1	16166-896-005	0927608
11	INSULATOR, CARBURETOR	●				●	●			-------	-------	1	16211-896-000	0927616

G100
G100K1
G100K2

Ref. No.	DESCRIPTION (BLOCK NO. E-11)	G100	G100K1	G100K2	QA	QAF	QAH	QA2	SMD2	ENGINE SERIAL NUMBER FROM	TO	QTY REQ	PART NUMBER	HONDA CODE
11	INSULATOR, CARBURETOR	●				●	●			------	------	1	16211-896-306	4026209
		●				●	●			------	------	(1)	16211-896-306	4026209
12	GASKET, INSULATOR	●				●	●			------	------	1	16212-896-000	0927624
	GASKET, INSULATOR	●				●	●			------	------	1	16212-896-306	4593596
13	GASKET, AIR CLEANER	●				●	●			------	------	1	16269-892-000	0865139
	GASKET, AIR CLEANER	●				●	●			------	------	1	16269-892-306	4513404
14	JET, MAIN (#45)	●				●	●			------	------	(1)	99101-124-0450	0947333
	JET, MAIN (#48)	●				●	●			------	------	(1)	99101-124-0480	0947341
	JET, MAIN (#50)	●				●	●			------	------	(1)	99101-124-0500	0947358
	JET, MAIN (#52)	●				●	●			------	------	(1)	99101-124-0520	0897736
	JET, MAIN (#55)	●				●	●			------	------	1	99101-124-0550	0635458

CYLINDER HEAD ASSEMBLY - MODELS 960r-970r-990r

RYOBI AMERICA CORP.

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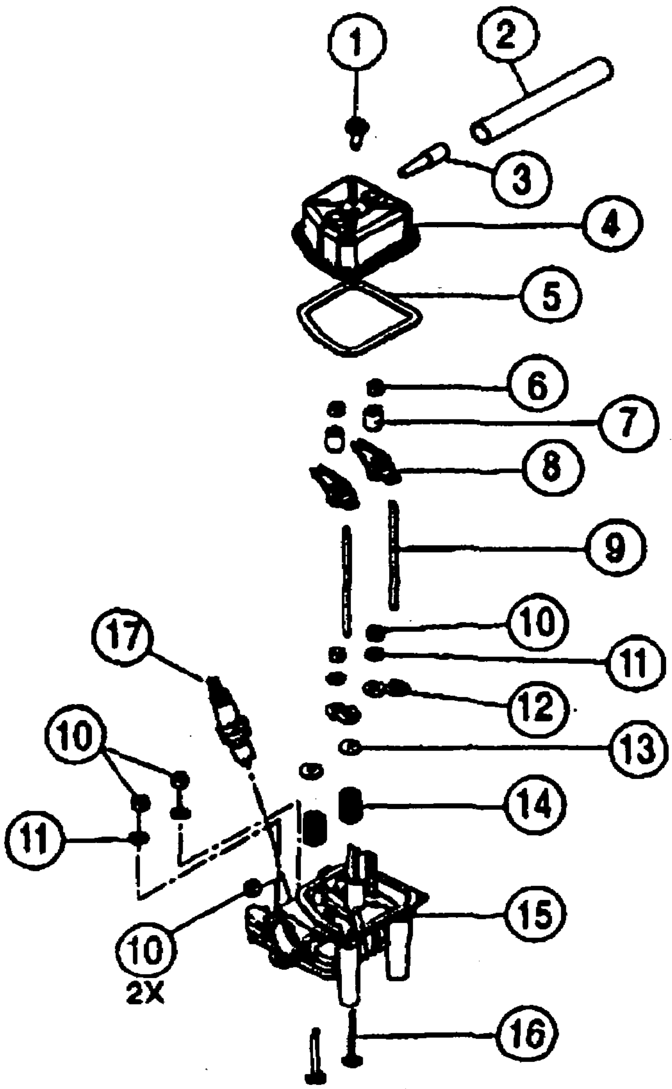
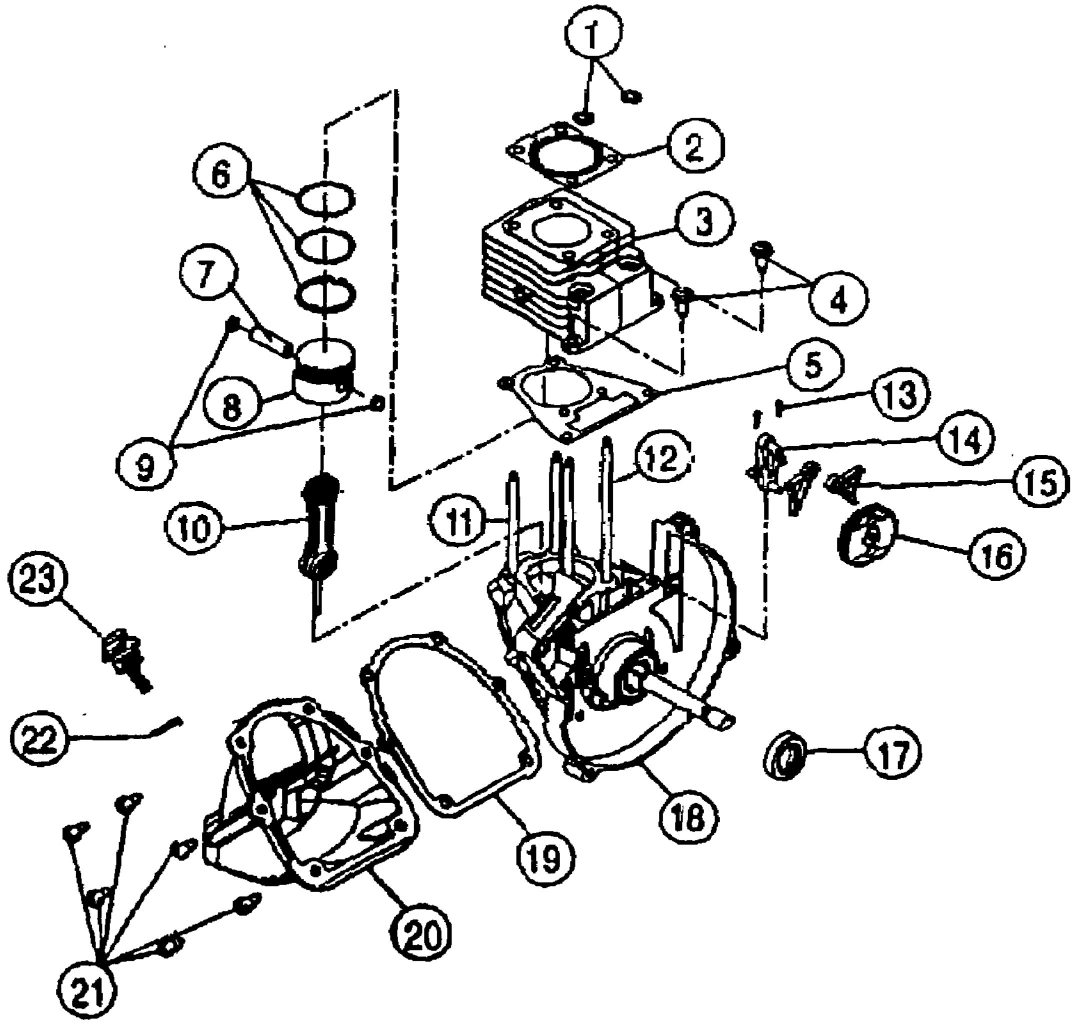


Item	Part No.	Description
1	181025	Screw, Valve Cover
2	181026	Hose, Breather
3	181027	Breather Assembly
4	181028	Cover, Valve
5	181029	Gasket, Valve Cover
	181030	Nut, Rocker Adjusting
[illegible]	181031	Pivot, Rocker Arm
8	181032	Arm, Rocker
9	181033	Rod, Push
10	181034	Nut, Hex 5M
11	181035	Washer
12	181036	Guide, Push Rod
13	181037	Retainer, Valve Spring
14	181038	Spring, Valve
15	181039	Head, Cylinder
16	181040	Valve
17	180852	Spark Plug
*	181041	Cylinder Head Assembly (items 13-16)
*	181042	Short Block Assembly (all items from pages 2 & 3)

* not shown

CYLINDER & CRANKCASE ASSEMBLY - MODELS 960r-970r-990r

(Serial no. 403026296 and greater)



Item	Part No.	Description
1	181000	O-Ring, Push Rod Tube
2	181001	Gasket, Cylinder Head
3	181002	Cylinder
4	181003	Screw, M5 X 18.7mm
5	181004	Gasket, Cylinder
6	181005	Piston Ring Set
7	181006	Pin, Wrist
8	181007	Piston
9	181008	Button, Wrist Pin
10	181009	Rod, Connecting
11	181010	Cylinder Stud (83.5mm)
12	181011	Cylinder Stud (115.5mm)
13	181012	Screw, Cam Bracket
14	181013	Bracket, Cam
15	181014	Follower, Cam
16	181015	Cam Gear
17	181016	Seal
18	181017	Crankcase W/Power Shaft (Includes items 11, 12 & 17)
19	181018	Gasket, Oil Pan
20	181019	Pan, Oil
21	181020	Screw, M5 X 15.8mm (6 required)
22	181021	O-Ring
23	181022	Plug, Oil Fill (includes item 22)
*	181023	Piston and Rod Assembly (items 6-10)
*	181024	Engine Gasket Kit

* not shown

CARBURETOR & MUFFLER ASSEMBLIES - MODELS 960r-970r-990r

(Serial no. [illegible])

RYOBI AMERICA CORP.

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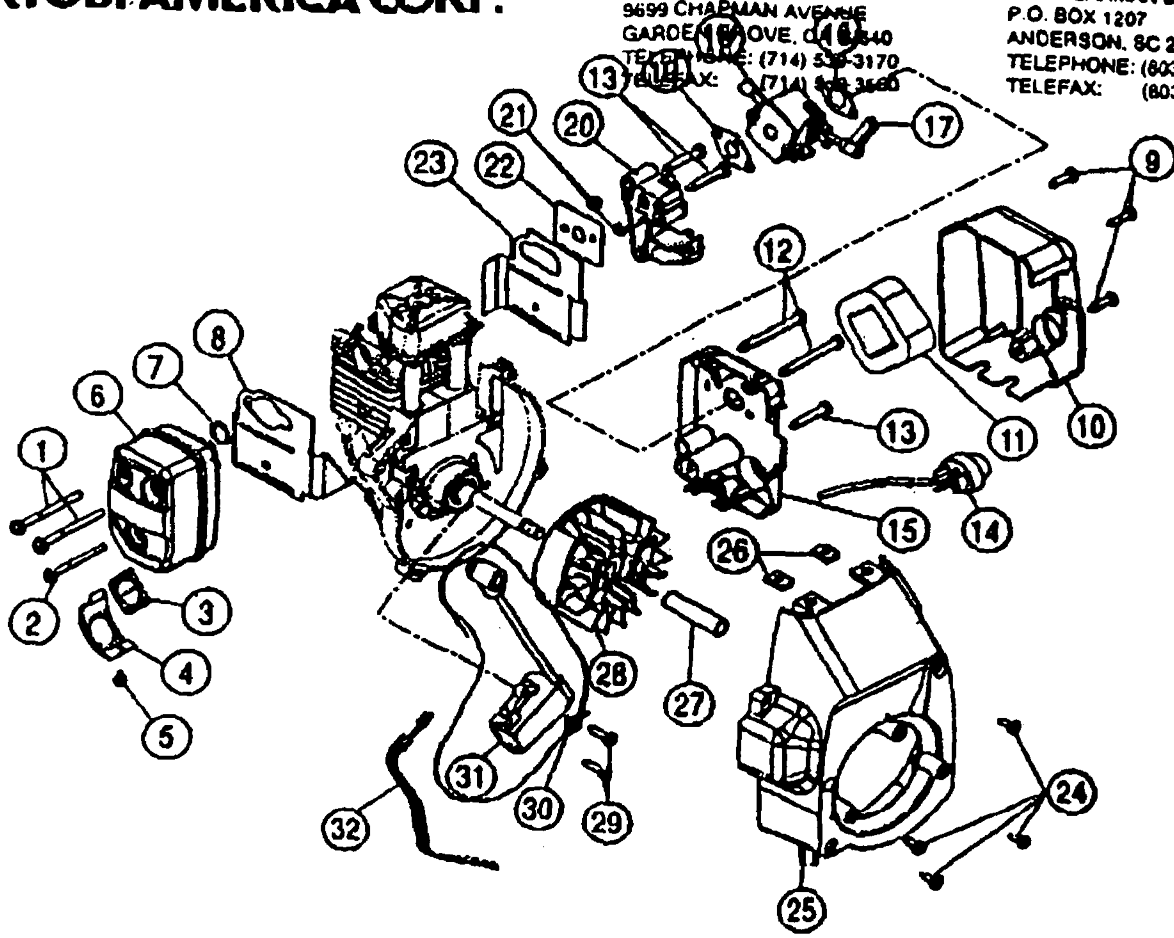


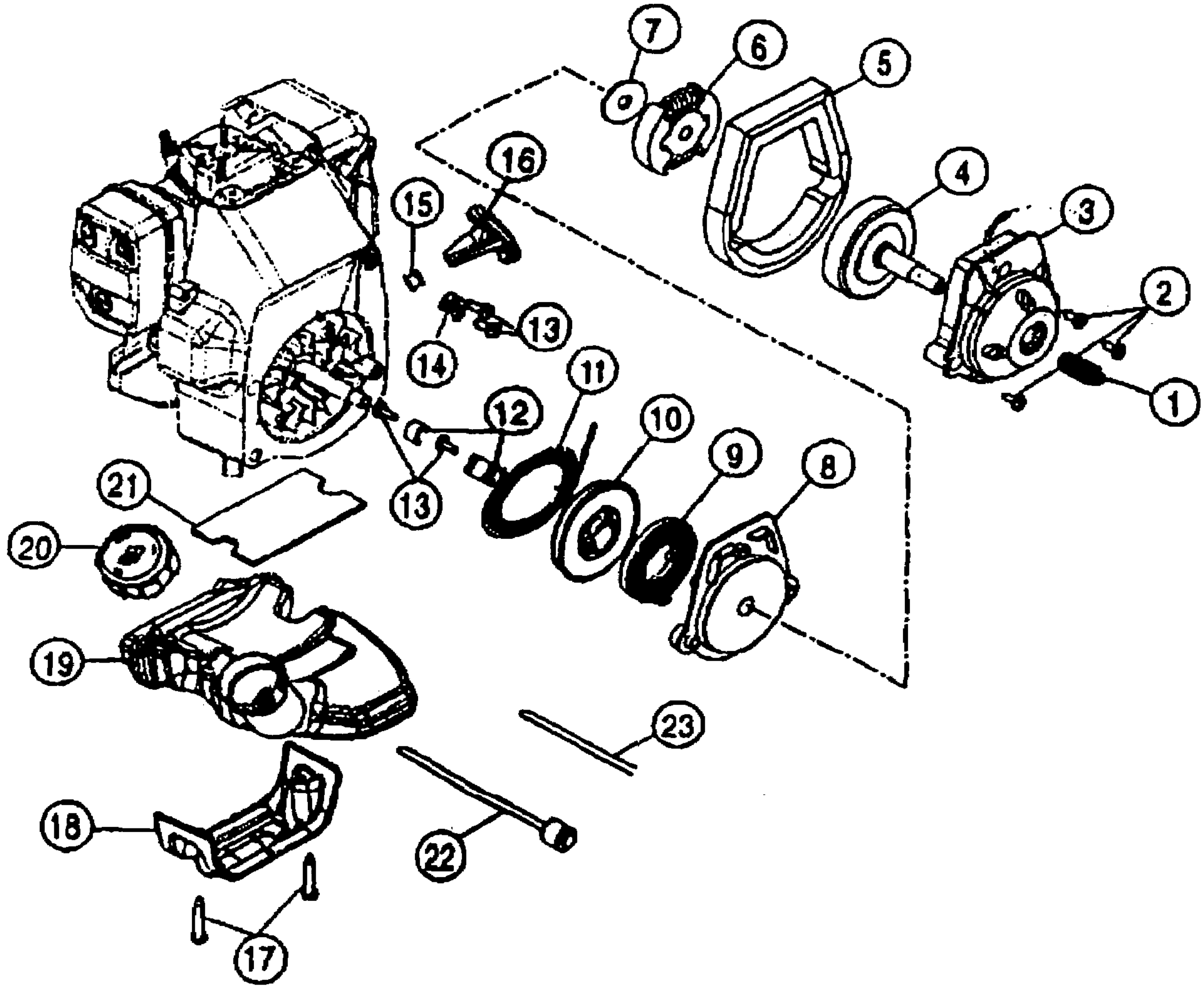
Item	Part No.	Description
1	181043	Screw, Muffler Mounting
2	181044	Screw, Muffler Mounting
3	180890	Screen, Spark Arrestor
4	181045	Cover, Screen
5	181046	Screw, Screen Cover
6	181047	Muffler (includes items 1-5 & 7)
7	181048	Gasket, Muffler
8	181049	Baffle, Muffler
9	181050	Screw, Air Filter Cover
10	181051	Cover, Air Filter
11	180350	Filter, Air
12	181052	Screw, Air Filter Base (52.5mm)
13	181053	Screw, M5 X 29mm
14	181054	Primer and Line Assembly
15	181055	Base, Air Filter
16	181056	Gasket
17	181057	Lever, Choke
18	181058	Carburetor W/Choke Lever
19	181059	Gasket

Item	Part No.	Description
20	181060	Insulator, Carb Mount
21	181034	Nut, Hex 5M
22	181061	Gasket, Intake
23	181062	Baffle, Intake
24	181003	Screw, M5 X 18.7mm
25	181063	Housing, Fan
26	181064	Nut, Tinnerman
27	181065	Spacer
28	153624	Flywheel
29	181066	Screw, Module
30	611063	Tab, Ground
31	181067	Module, Ignition
32	181094	Lead, Wire 18" (2 required)
*	610676	Key, Flywheel
*	180142	Flywheel Starter Pawl Repair Kit
*	181068	O.E.M. Carburetor Repair Kit
*	181069	Gasket-Diaphragm Repair Kit

* not shown

CLUTCH, STARTER MODULE & FUEL TANK ASSEMBLIES - MODELS 960r-970r-990r

(Serial no. 403026296 and greater)



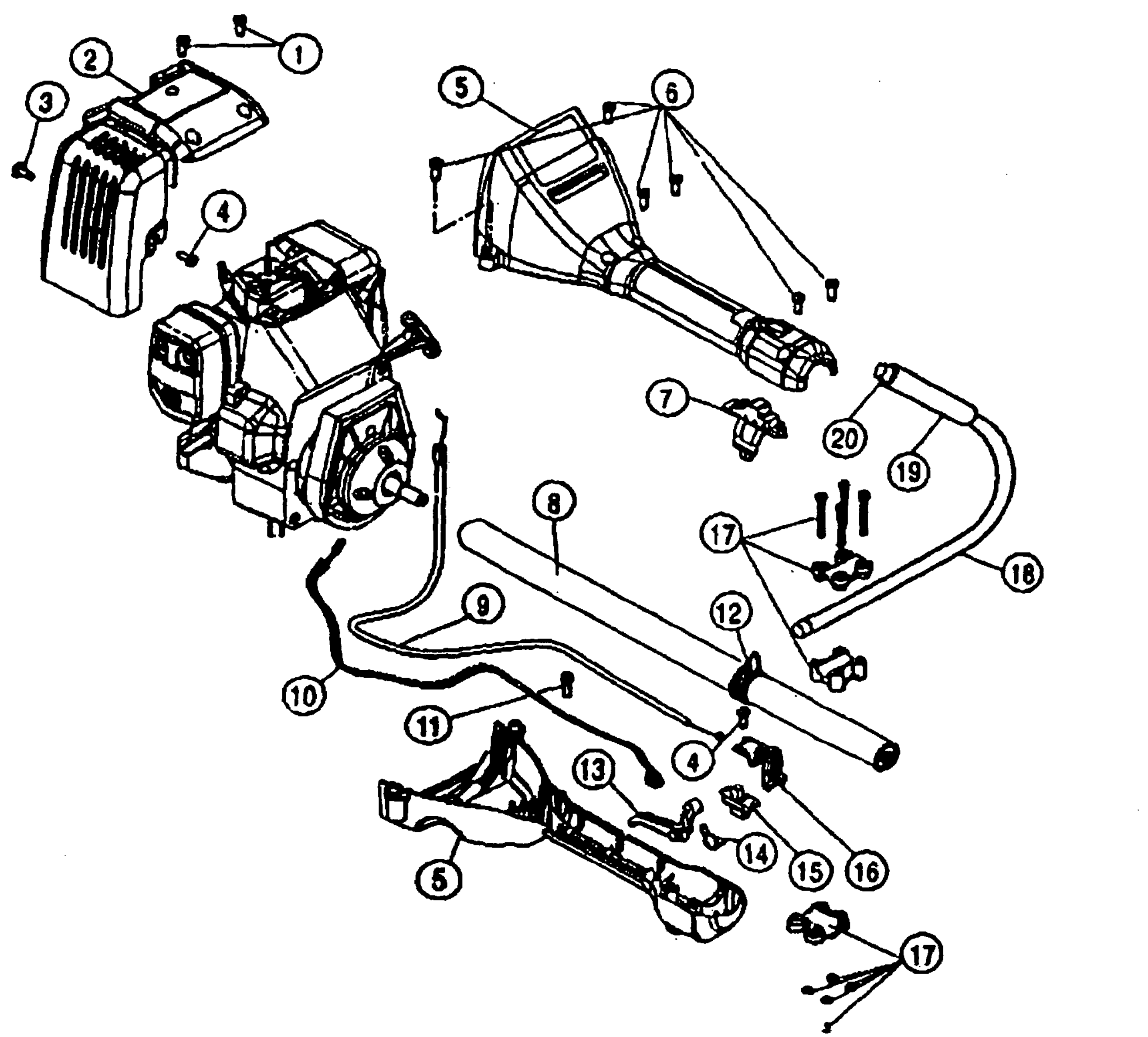
Item	Part No.	Description
1	612468	Spring, Compression (970r and 990r only)
2	181070	Screw, M5 X 32mm
3	181071	Housing, Clutch
4	180232	Drum, Clutch
•	181102	Clutch Housing Assembly W/Drum (Items 3 & 4)
5	181072	Isolator
6	181073	Clutch
7	181074	Washer, Clutch
•	181087	Starter Module Assembly (Items 8-13, 15 & 16)
	181075	Housing, Starter
9	613102	Spring, Starter
10	180635	Pulley, Starter
11	613103	Rope, Starter

Item	Part No.	Description
12	181076	Retainer, Starter Pulley
13	181077	Screw, M4 X 12.7mm
14	181078	Retainer, Rope Guide
15	611061	Guide, Rope
16	181079	Handle, Starter
17	181080	Screw, Fuel Tank Bracket
18	181081	Bracket, Fuel Tank
19	181082	Tank, Fuel (Includes Items 20, 22 & 23)
20	181083	Cap, Fuel
21	181084	Pad, Fuel Tank
22	181085	Fuel Line Assembly W/Filter
23	181086	Line, Fuel Return

not shown

HANDLE & UPPER BOOM ASSEMBLY - MODELS 960r-970r-990r

(Serial no. 403026296 and greater)



Item	Part No.	Description
1	181020	Screw, M5 X 15.8mm
2	181088	Cover, Engine
3	181089	Screw, M5 X 15.78mm SEMS
4	181104	Screw, Engine Cover
5	181090	Handle, Assembly
6	181070	Screw, M5 X 32mm
7	181091	Slide, Switch
8	181092	Housing, Upper Drive (970r and 990r only)
8	181105	Housing, Upper Drive (960r only)
9	181093	Cable, Throttle
10	181094	Lead, Wire 18" (2 required)
11	181095	Screw, Anti-Rotation
12	610327	Clip, Shoulder Strap
13	181096	Trigger
14	610314	Spring
15	181097	Switch
16	181098	Retainer, Switch & Trigger
17	683295	Handle Bracket Assembly
18	181099	J-Handle Assembly (Items 19 & 20)
19	612831	Grip
20	612021	Tube Closure
*	181103	Decal Kit

* not shown

LOWER BOOM & CUTTING HEAD ASSEMBLY - MODEL 960r

RYOBI AMERICA CORP.

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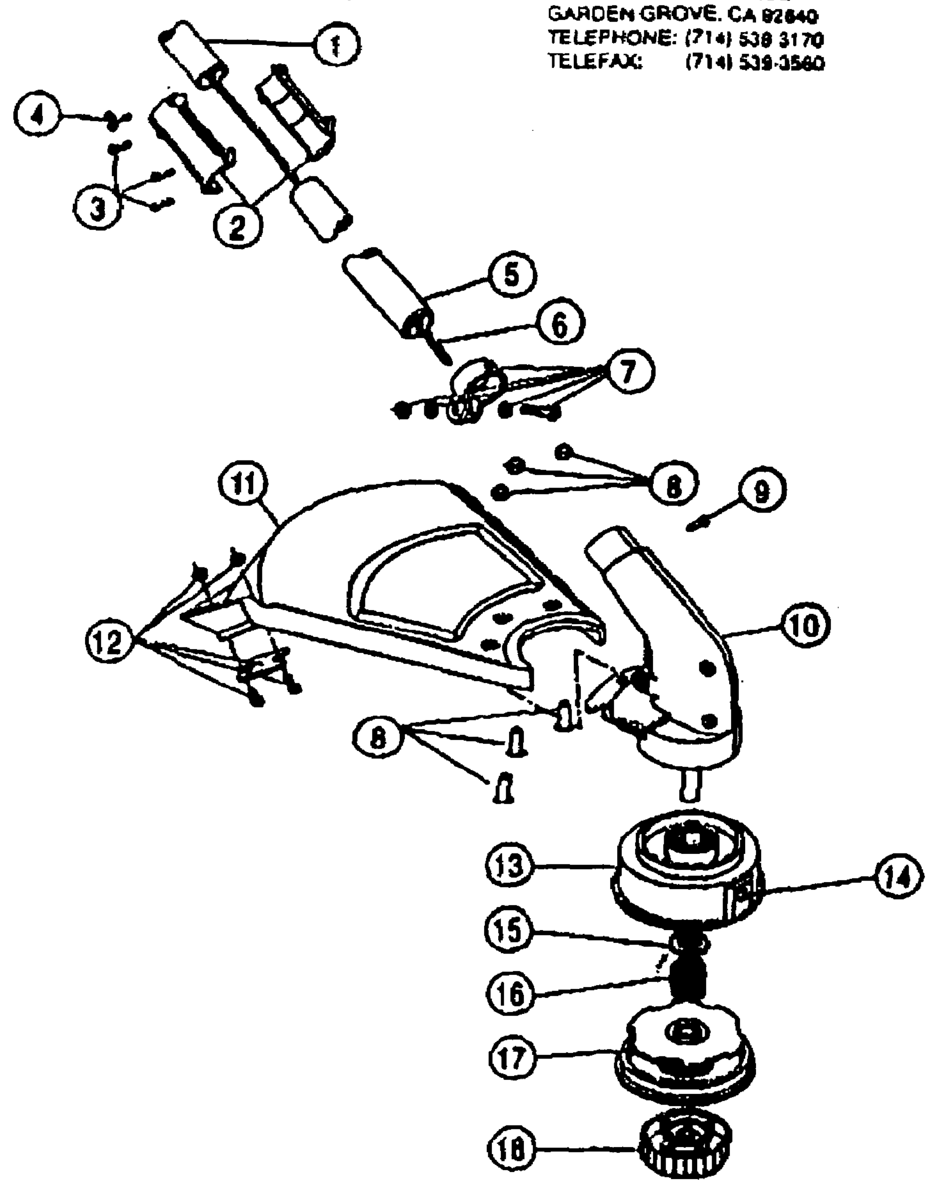


Item	Part No.	Description
1	181105	Housing, Upper Drive
2	153671	Split Boom Coupling Set
3	683074	Screw, Coupling Set
4	147643	Screw, Wing (qty 1)
5	181108	Housing, Lower Drive
6	180406	Shaft, Flexible Drive
7	153597	Clamp Assembly
8	180547	Hardware, Guard Mounting
9	145569	Screw, Anti-Rotation
10	180549	Gearbox
11	180548	Guard, Cutting Head
12	180553	Blade Assembly
13	153619	Spool, Outer W/Eyelet
14	145568	Eyelet
15	610660	Retainer
16	610317	Spring
17	153600	Reel, Inner
18	153066	Bump Head Knob Assembly

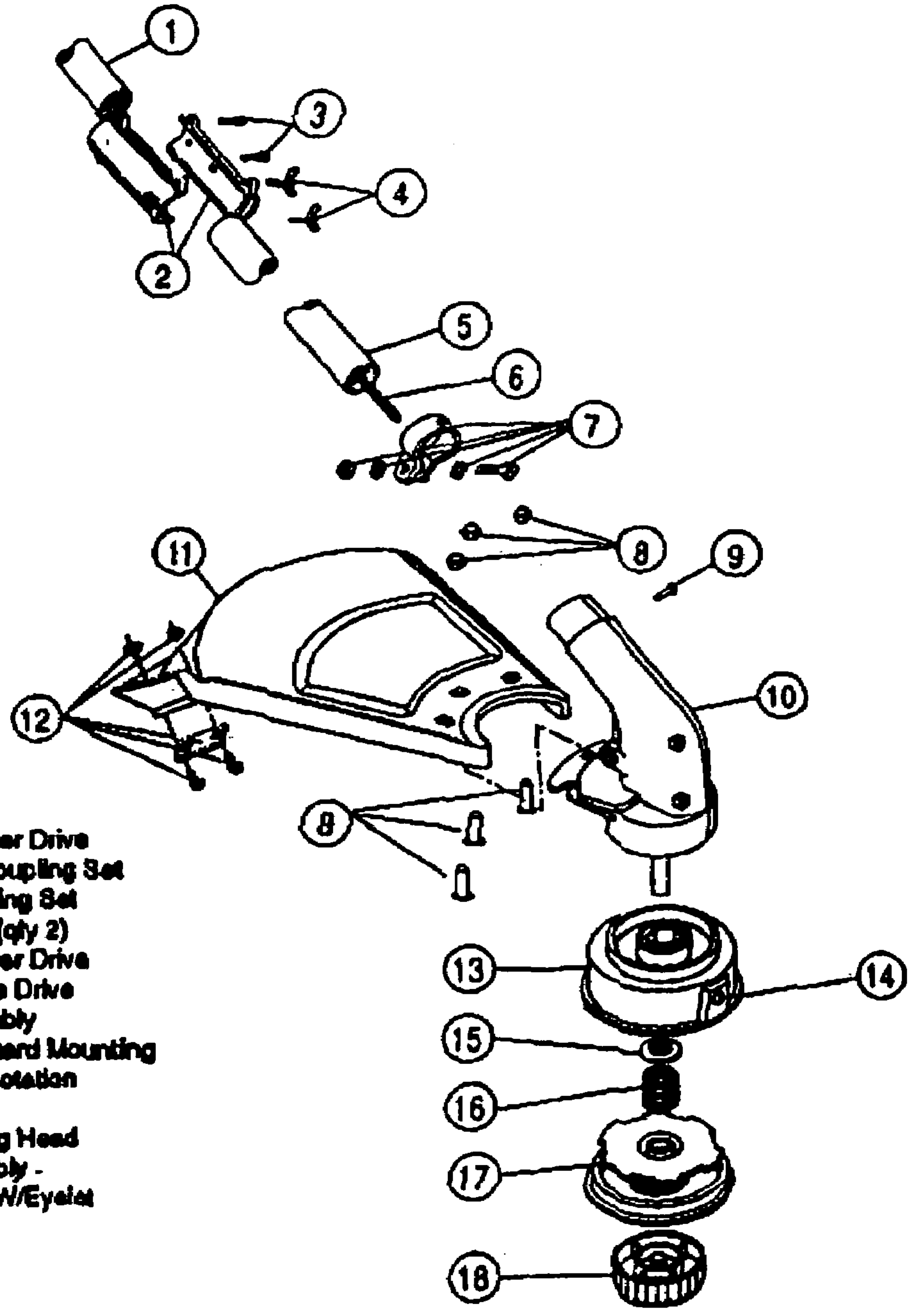
Optional Accessories

*	610375	Monofil Cutting Line (50 ft)
*	153577	Spool and Line (30 ft) Assembly
*	682075	Shoulder Strap Assembly
*	181100	Oil, SAE 30 100ml Bottle
*	181101	Spout, Oil Fill

* not shown

LOWER BOOM & CUTTING HEAD ASSEMBLY - MODEL 970r

(Serial no. 403026296 and greater)



Item	Part No.	Description
1	181092	Housing, Upper Drive
2	683605	Split Boom Coupling Set
3	683606	Screw, Coupling Set
4	683607	Screw, Wing (qty 2)
5	180689	Housing, Lower Drive
6	683608	Shaft, Flexible Drive
7	153597	Clamp Assembly
8	180547	Hardware, Guard Mounting
9	145569	Screw, Anti-Rotation
10	180549	Gearbox
11	180548	Guard, Cutting Head
12	180553	Blade Assembly -
13	153619	Spool, Outer W/Eyelet
14	145568	Eyelet
15	610660	Retainer
16	610317	Spring
17	153600	Reel, Inner
18	153068	Bump Head Knob Assembly

Optional Accessories

*	610376	Monofil Cutting Line (50 ft)
*	153577	Spool and Line (30 ft) Assembly
*	682075	Shoulder Strap Assembly
*	181100	Oil, SAE 30 100ml Bottle
*	181101	Spout, Oil Fill

* not shown

LOWER BOOM & CUTTING HEAD ASSEMBLY - MODEL 990r

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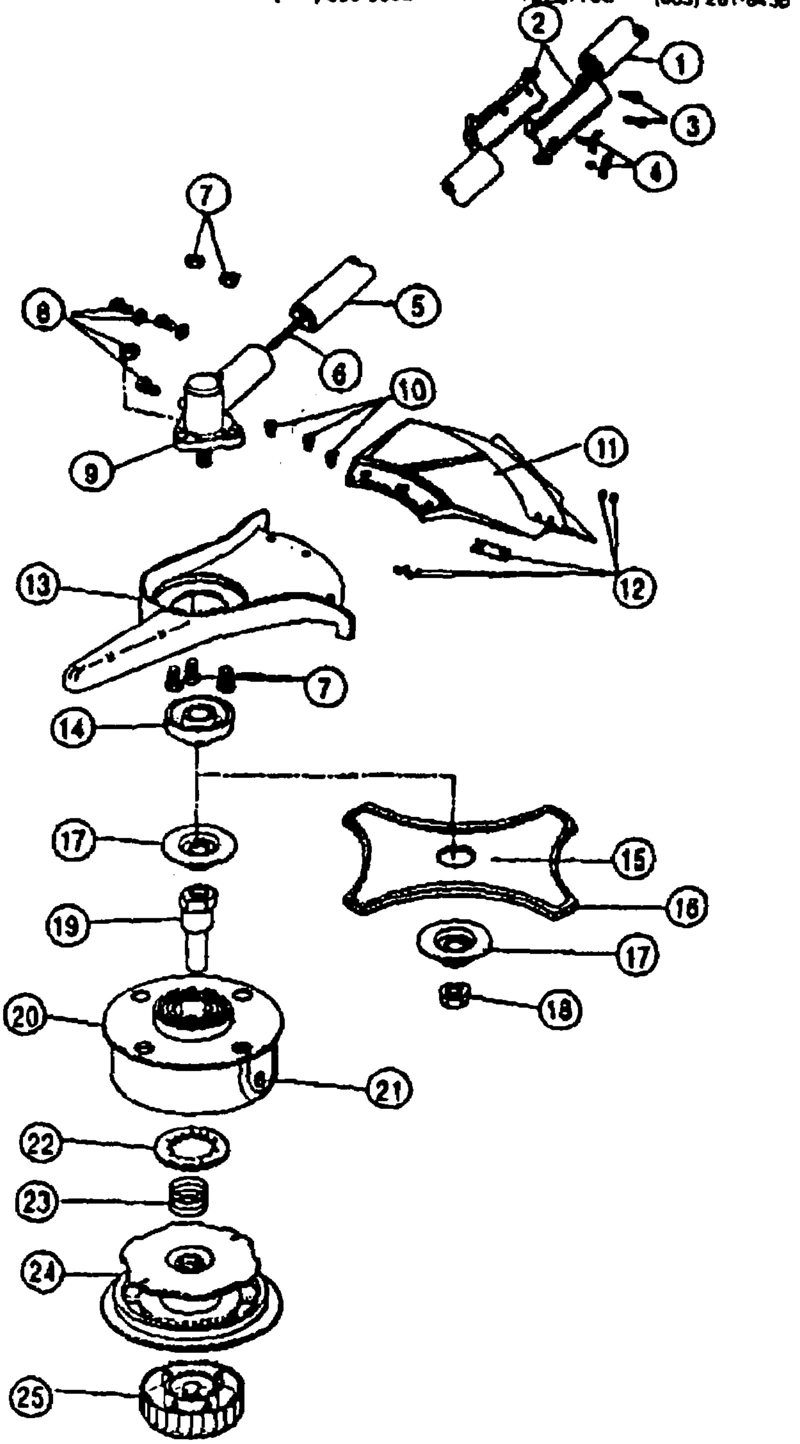

Item	Part No.	Description
1	181092	Housing, Upper Drive
2	683605	Split Boom Coupling Set
3	683606	Screw, Coupling Set
4	683607	Screw, Wing (qty 2)
5	180804	Housing, Lower Drive
6	613300	Shaft, Flexible Drive
7	147539	Hardware, Brush Blade Guard Mounting
8	147677	Mounting Hardware & Grease Plug Assembly
9	147488	Gearbox (items 8, 14, 17 and 18)
10	683304	Screw, Guard Mounting
11	180367	Guard, Cutting Head
12	682061	Blade Assembly
13	147492	Guard Mount
14	147489	Driver
15	145873	Blade, Brush (includes item 16)
16	147670	Cover, Blade
17	147490	Washer, Retainer
18	147491	Nut, Lock
19	612483	Shaft, Spool
20	147494	Spool, Outer W/Eyelet
21	145566	Eyelet
22	612026	Retainer
23	610636	Spring
24	147495	Reel, Inner
25	180614	Bump Head Knob Assembly
*	147299	Locking Rod Tool
*	682075	Shoulder Strap Assembly

Optional Accessories

*	180120	Monofilal Cutting Line (50 ft)
*	147345	Spool and Line Assembly (40 ft)
*	147498	Complete Head Assembly (items 19-25)
*	180014	Blade Retaining Kit (items 17 and 18)
*	181100	Oil, SAE 30 100ML Bottle
	181101	Spout, Oil Fill

* not shown

ENGINE PARTS - RYOBI 720r

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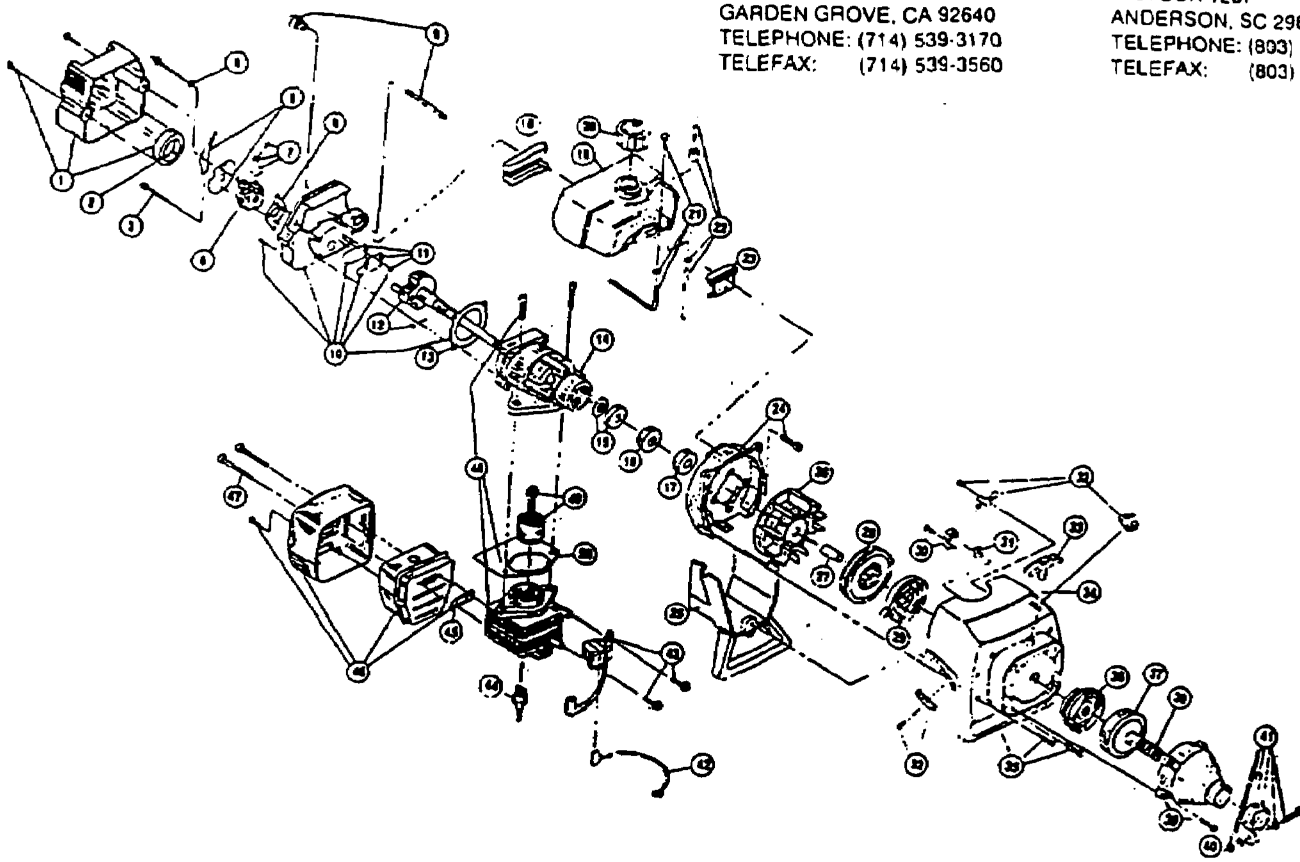

Item	Part No.	Description
1	180349	Carburetor/Air Cleaner Cover Assembly (includes item 2)
2	180350	Air Cleaner Filter
3	180351	Carburetor Mounting Screw Assembly
4	180352	Wavey Washer
5	180353	Choke Lever and Plate
6	147572	Carburetor Assembly
7	682048	Throttle Adjustment Assembly (Walbro)
7	147640	Throttle Adjustment Assembly (Tillotson)
8	610675	Carburetor Gasket (10 pack)
9	683974	Primer and Hose Assembly
10	180354	Carburetor Mount Assembly (includes 11 and 13)
11	147573	Reed Assembly
12	180022	Power Shaft Assembly
13	612115	Carburetor Mount Gasket (10 pack)
14	180026	Crankcase Service Assembly (items 12, 14-17)
15	682041	Inner Bearing Assembly
16	610309	Seal
17	610308	Outer Bearing Assembly
18	612134	Rear Mounting Pad
19	147580	Fuel Tank Assembly (includes items 20-22)
20	180000	Fuel Cap Assembly
21	147290	Return Line Assembly
22	682039	Fuel Line Assembly
23	145308	Front Mounting Pad
24	153520	Shroud Assembly
25	683078	Shroud Extension and Stand
26	153624	Flywheel Assembly
27	145918	Spacer
	683856	Recoil Pulley Assembly
	613102	Recoil Spring
30	153644	Pulley Retainer Assembly
31	611061	Rope Guide
32	180035	Switch Assembly
33	610300	Pull Handle
34	613103	Rope
35	180097	Starter Housing Assembly
36	153591	Clutch Rotor Assembly
37	153592	Clutch Drum Assembly
38	612468	Spring
39	683601	Clutch Cover Assembly
40	145888	Clutch Cover Screw Assembly
41	153597	Upper Clamp Assembly
42	180036	Wire Lead
43	683390	Module Assembly
44	610311	Spark Plug
45	610672	Exhaust Gasket (10 pack)
46	180119	Muffler Assembly (includes 46 and 48)
47	147575	Muffler Mounting Bolt Assembly
48	180063	Cylinder Assembly
49	147012	Piston and Rod Assembly
50	145564	Cylinder Gasket (10 pack)
*	180034	Engine Hardware Kit
*	180011	Engine Gasket Kit
*	153308	O.E.M. Carburetor Repair Kit (Walbro)
*	147170	O.E.M. Carburetor Repair Kit (Tillotson)
*	153309	Gasket Diaphragm Repair Kit (Walbro)
*	147171	Gasket Diaphragm Repair Kit (Tillotson)
*	682507	Piston Ring
*	180027	Short Block Assembly (items 12, 14-17, 48-50)
*	610678	Flywheel Key (10 pack)
*	147544	Starter Housing Screw Set

* not shown

The above part numbers are for serial numbers 203096321 and greater.

BOOM & TRIMMER PARTS - RYOBI 720r

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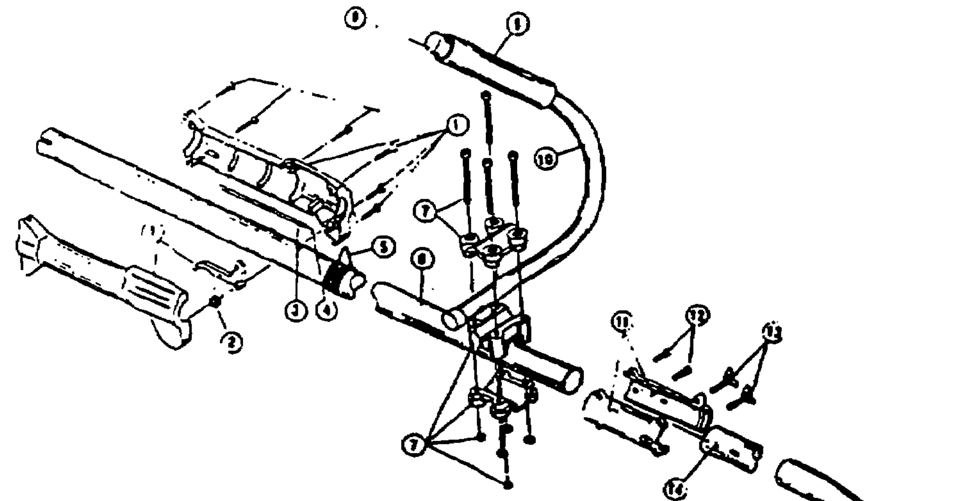

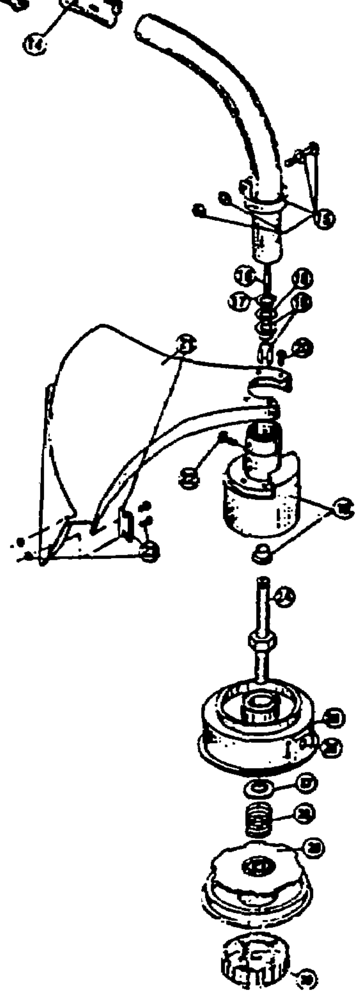

Item	Part No.	Description
1	180277	Throttle Housing and Trigger Assembly
2	610314	Throttle Trigger Spring
3	180021	Throttle Cable Housing Assembly
4	180127	Throttle Cable
5	610327	Shoulder Strap Clamp
6	683603	Drive Shaft Housing Assembly
7	683295	Handle Bracket Assembly
8	612021	Tube Closure
9	612831	Grip
10	683815	J-Handle Assembly (includes items 8 and 9)
11	683605	Split Boom Coupling Set
12	683606	Coupling Bolt Assembly
13	683607	Adjustment Knob Set
14	683604	Lower Drive Shaft Housing Assembly
15	153597	Lower Clamp Assembly
16	683608	Lower Flexible Drive Shaft
17	145570	Retaining Ring
18	145567	Washer
19	153312	Bushing Housing Assembly
20	153318	Guard Mounting Screw Assembly
21	683274	Guard and Blade Assembly
22	145569	Anti-Rotation Screw
23	682061	Blade Assembly
24	153313	Spool Shaft
25	153619	Outer Spool and Eyelet Assembly
26	145566	Eyelet
27	610660	Retainer (10 pack)
28	610317	Spring
29	153600	Inner Reel
30	153066	Bump Head Knob Assembly

Optional Accessories

*	610375	Monoflail Cutting Line, 50 ft.
*	153577	Spool and 30 ft. Line (dual)
*	147823	Complete Cutting Head Assembly (includes items 15, 17-30)
*	682075	Shoulder Strap Assembly
*	147541	IDC or Ryobi 2-Cycle Oil (4. oz. can)

* not shown

APPENDIX C:

ADDITIONAL TECHNOLOGIES TO REDUCE EMISSIONS IN HANDHELD ENGINES

This appendix describes in detail additional technologies to reduce emissions in handheld engines.

Exhaust Control Valve

Hsieh et al (1992), Tsuchiya et al (1980), and Duret and Moreau (1990) have demonstrated the potential of exhaust charge control valves in small two-stroke engines. Results of their studies show that significant reductions in HC emissions and fuel consumption can be achieved, as well as a reduction in unstable combustion at light load. A study done by Yamagishi et al. (1972) concluded that misfire is most likely to occur at a delivery ratio less than 0.3. It was also observed that the scavenging losses were low but the exhaust HC concentration was still high. At a low delivery ratio, the trapping efficiency was higher and resulted in lower scavenging losses. However, at very low delivery ratios corresponding to light load and idle, misfire or irregular combustion were occurring - resulting in high HC emissions even though the scavenging losses were low.

Tsuchiya et al. identified the delivery ratio at which a rapid increase in irregular combustion occurs (defined as the critical delivery ratio) as 0.2. This is very similar to the finding of Hsieh et al that 0.25 was the critical delivery ratio. With exhaust charge control, Hsieh et al. found that the critical delivery ratio decreases from 0.25 to 0.20 and 0.15 at low and medium engine speeds (1,500 and 3,000 rpm), respectively. Thus, the exhaust charge control technique effectively reduced irregular combustion under light-load conditions. Hsieh et al. found that HC emissions and fuel consumption were reduced by 30% and 6% respectively when the exhaust charge control technique was used in a test engine. Also, at the same delivery ratio, the engine with exhaust charge control produced higher power output. Duret and Moreau found that a 60% reduction in HC emissions and 20% reduction in fuel consumption could be achieved through the use of an exhaust charge control valve.

Honda has incorporated a "Revolutionary Controlled Exhaust Valve (RC Valve)" in a 150 cc two-stroke motorcycle model equipped with a capacitive-discharge ignition, computerized controller and servo motor to attain high power efficiency at low and high speed conditions. Although the "RC Valve" is intended to improve engine performance, it can also serve as an emissions control device.

Queen's University of Belfast - At the Queen's University of Belfast (QUB), Magee et al. have developed an "air head" scavenging system that uses the stratified scavenging concept in a 50 cc two-stroke engine (Magee et al., 1993). In this engine, two charge inlets are used: one for pure air only, and the other for the regular carburetion intake. Controlled by reed valves, the pure air is inducted into the top of the transfer passages through an auxiliary air inlet, while a mixture of air and fuel is inducted into the crankcase. At wide open throttle and maximum secondary air flow, Magee et al reported a 30% reduction in HC emissions and a 10% improvement in brake specific fuel consumption throughout the speed range. The fuel trapping efficiency for the engine with the stratified scavenging system was improved by 10%, and the performance (power and BMEP) of the engine also improved. However, in another paper on the same study (Magee et al., 1993-2), it was reported that the engine experienced some bad performance characteristics at light and part-load conditions, with BMEP less than 3.5 bar. It was suspected that this was due to the low delivery ratio, which was around 0.25-0.35 (Magee et al, 1993-2).

Ricardo - Recently, Ricardo Consulting Engineers PLC published a paper discussing their stratified charging concept (RSCE) (Glover and Mason, 1995). This system employs quite similar principles to the QUB's concept. In the Ricardo system, the fuel is initially delivered to a specially-shaped rear transfer port, which serves as a storage as well as a fuel preparation area. During the initial of the scavenging process, pure air is driven from the crankcase to the combustion chamber through two lateral transfer ports. Controlled by the piston, the rear transfer port is opened almost at the end of the scavenging process. This allows some remaining pure air to flow through the port and mix with the fuel, carrying the fuel/air mixture into the combustion chamber. Ricardo has demonstrated this concept in a 50 cc scooter engine. Emission results indicate that substantial HC emission reduction is achieved only during medium/high engine speed/load conditions. The stratified charging engine was found to be more unstable than the baseline engine, and it produced as much HC emissions as well.

Indian Institute of Petroleum - Saxena et al. (1989) of the Indian Institute of Petroleum have developed a 150 cc engine using the stratified scavenging concept with a dual intake system. The secondary pure air is induced into the transfer passages through reed valves. The primary and secondary air supplies were chosen to be 50% each, as Saxena et al's experiment showed that the HC emission reductions and BSFC level off after the supply of secondary air exceeded 50%. At full load conditions, the results showed 25 to 30% reductions in HC emissions, as well as about 10% improvement in BSFC throughout the range of air/fuel ratios tested (0.75-1.05). The performance of the engine was also improved slightly. Saxena et al. also showed the effect engine load on HC emissions and BSFC. Lower HC emission reductions (13-16%) and BSFC (2-3%) were found at low-load conditions, while at high load the benefits were a more than 30% reduction in HC emissions and a 10% improvement in BSFC. Under simulated road-load conditions (over a range of speeds) at an air/fuel equivalence ratio of 0.85, the HC emission reductions varied from 20 to 30% and BSFC improvements varied from 5 to 10%, depending on the engine speeds. Again, lower HC reductions and BSFC improvements were found at lower road/speed conditions.

To explain the low HC emission reduction and BSFC improvement at low load conditions, Saxena et al. determined the fuel trapping efficiency and scavenging losses from both engines for a range of delivery ratios (0.2-0.6). High fuel trapping efficiencies and low scavenging losses were observed at low delivery ratio (light load conditions), similar to Yamagishi's findings; and low fuel trapping efficiency and high scavenging losses were found at higher delivery ratios. Compared with the base engine, the fuel trapping efficiency was improved and the scavenging losses were decreased for the stratified scavenging engine throughout the range of delivery ratios. However, minimal improvements in both fuel trapping efficiency and scavenging losses were achieved at low delivery ratios or light load conditions. With these results, Saxena et al. concluded that at low delivery ratio the losses due to poor combustion were high and the scavenging-through losses were low, and therefore, minimal HC emission reduction could be achieved with this dual-intake stratified scavenging engine.

India Institute of Technology - Babu et al. (1993), of the Indian Institute of Technology, also investigated the stratified scavenging approach. Similar to the system investigated by Saxena et al, Babu et al. used a second intake system to induct pure air through reed valves into the transfer passages. A difference was that the secondary intake system was set up to be able to supply compressed air. The system was applied on three engines, with engine displacements ranging from 55 cc to 250 cc. A control valve was used in the secondary air intake system to regulate or vary the air flow through the intakes. A compressor was set up to supply a slightly higher pressure air flow through the reed valves if needed. Also, three openings were selected to regulate the air flow through the reed valves to determine the effect of the amount of secondary air induced into the engine. In general, the results showed reductions in HC emissions of about 25%, and as much as 17% improvement in the brake thermal efficiency due to the reduction in scavenging losses. When an optimum amount of compressed air was supplied to the secondary air intake, the improvement in brake thermal efficiency and reduction in HC emission were even higher; especially at the full throttle condition. This was mainly due to the reduction in secondary air flows during high throttle conditions when the secondary air was induced at the atmospheric pressure. In this study, it was also concluded that an optimum secondary air flow rate was necessary in order to obtain maximum performance and emission benefits.

Catalyst

Graz University of Technology - The Graz researchers focused on reducing exhaust emissions from two-stroke moped, motorcycle and chainsaw engines by using catalytic converters, as well as by improving the thermodynamic characteristics of the engine, through changes in gas exchange and fuel handling systems, cylinder and piston geometry, and exhaust and cooling systems. Table I shows the effects of catalytic converters on emissions from production, lean-burn production, and advanced moped engines tested under the ECE-15 driving cycle. As the table shows, addition of a catalytic converter to the conventional moped reduced HC and CO emissions by 64 and 61%, respectively. The relatively low efficiency in this case was due to the rich air-fuel mixture used in the conventional moped, which limited the ability of the catalyst to oxidize the excess HC.

Comparing baseline emissions between the conventional moped and the lean-burn production moped, Table I shows that the lean-burn moped produced about 80% less CO and 18% less HC emissions, without the catalytic converter. The efficiency of the catalytic converter was also increased, due to the higher oxygen concentration in the exhaust. In this case, the CO and HC reductions were 75% and 89%, respectively. Durability testing on two production lean-burn Puch mopeds equipped with catalytic converters showed that the HC emissions increased by 42% while the CO emissions were reduced by 31% after 10,200 km or about 450 hours. At that

Table I: Emission data for production and advanced moped engines with and without catalyst tested under ECE-R47 driving cycle.

Engine Configuration		Emissions (g/km)		
		CO	HC	Nox
Production Puch	Without Catalyst	5.6	3.9	n/a
	With Catalyst	2.2	1.4	n/a
Production Puch Superm-axi, Lean-Burn	Without Catalyst	1.1	3.2	n/a
	With Catalyst	0.28	0.34	n/a
Advanced 1.2 hp	Without Catalyst	1.311	2.432	0.038
	With Catalyst	0.036	0.094	0.031
Advanced 2.7 hp	Without Catalyst	0.771	3.205	0.090
	With Catalyst	0.093	0.116	0.065
	With Dual Catalyst	0.022	0.037	0.067

point, the emission levels still met the Swiss standards. Since the overall air-fuel mixture was rich, the catalyst oxidized HC to CO. The increase in HC and reduction in CO are consistent with a fairly rapid decline in catalyst efficiency with age. This would be expected, given the high operating temperature of the catalyst.

Table I also shows emission results for two advanced-technology moped engines of 1.2 and 2.7 HP. These engines were designed to operate near or lean of stoichiometric over almost the entire speed-load range. Addition of a catalytic converter to the 1.2 HP advanced moped engine reduced HC, CO and Nox emissions by 96, 97 and 18%, respectively. For the advanced 2.7 hp moped engine, the HC, CO, and Nox emissions were reduced by 96, 88 and 29% respectively when a catalytic converter was used. Data on catalyst temperatures were not provided in the Graz papers.

The Graz researchers also developed an advanced chainsaw engine equipped with a catalytic converter (Laimbock, 1991). In addition to the catalytic converter, this engine incorporated a new cylinder with four transfer ports, better cooling for the cylinder and cylinder head, and an optimized piston shape. Unlike the mopeds, this engine operated rich of stoichiometric. Engine maps showing emission results vs. speed and BMEP were presented in the Laimbock paper. For the chainsaw without catalyst, the engine map showed CO emissions ranging from 0.5 to 4.5%, HC emissions from 15,000 to 29,000 ppm, and Nox emissions from 30 to 400 ppm, depending on the load/speed conditions. For the chainsaw with catalyst, the CO, HC, and NOx emissions ranged from 0.5 to 4.7%, 7,000 to 17,000 ppm, and 3 to 300 ppm, respectively. These results translated into changes in CO emissions from about a 40% *increase* to an 80% reduction; 20 to 80% reduction in HC; and a 20 to 85% reduction for NOx. It should be noted that the NOx increased by 100% in a spot with high BMEP and air-fuel ratio slightly above stoichiometric.

For chainsaw engine emission development work, Graz University of Technology (G.U.T.) has developed a special emissions test cycle. This cycle is intended to simulate the main operation modes of chainsaws used by professional woodcutters, namely cutting and debranching operations. Laimbock (1993) reported that the typical emission results for standard production chainsaws, depending on the adjustment of the carburetor, were 3.7-5.9 g/min of HC emissions, 7.7-11.1 g/min of CO emissions, and 0.002-0.009 g/min of NOx emissions based on the GUT cycle. When the catalyst-equipped chainsaw was tested on GUT cycle, the emission results were 0.47 g/min for HC, 1.03 g/min for CO, and 0.028 g/min for NOx emissions. Comparing these results with the standard production chainsaws, average emission reductions for CO and HC were about 90%, while the NOx emissions slightly increased by 4%. Again, data on catalyst and tailpipe-out exhaust temperatures were not provided in the Graz papers.

It should be noted that in the work at Graz, catalytic converter efficiencies of 90% for HC and CO emissions were obtained mainly by the application of metal substrate technology along with lean air-fuel ratios.

<u>Industrial Technology Research Institute</u> - Researchers at ITRI have successfully retrofitted a catalytic converter to a 125 cc two-stroke motorcycle engine, and demonstrated both effective emissions control and durability (Hsien et al, 1992). The ITRI researchers evaluated the effects of catalyst composition and substrate, the cell density of the substrate, the converter size and installation location, and the use of secondary air injection on the catalytic effectiveness and engine performance. Their conclusions were as follows: 1) the use of a metal substrate is superior to the ceramic substrate of the same converter size in terms of conversion efficiency and engine performance, since the thin walls of the metal substrate result in a larger effective area and lower back pressure, 2) exhaust temperature profile, space availability, and the effects on engine exhaust tuning must be considered when installing the catalytic converter, 3) use of additional reduction catalyst Rh would improve the CO conversion efficiency in the rich air/fuel mixture environment typical of motorcycle two-stroke engines, 4) the cell density of the substrate should be less than 200 cpsi to minimize pressure loss and maintain engine power, 5) HC and CO conversion efficiencies increase significantly when secondary air is supplied, and 6) exhaust smoke opacity was also reduced with the use of the catalytic converter. This latter effect was due to the catalytic oxidation of the lubricating oil vapor in the catalytic converter. This effect has also been observed in other engines (Pfeifer et al., 1993).

In a more recent study, ITRI retrofitted a catalytic converter to a two-stroke scooter engine, together with fuel injection and skip-firing at idle. Adding the catalytic converter to the other emission control techniques improved the overall emissions control efficiency from 58.2% to 92.8% for HC, and from 56.8 to 97.6% for CO emissions. Efficiency improved only slightly with the use of secondary air. This is because the fuel-injected engine tested was able to operate with a lean mixture overall, so that sufficient oxygen was available in the catalytic converter even without the air injection.

Advanced Fuel Metering Systems

Precise metering of air and fuel can improve engine performance and fuel consumption and reduce exhaust emissions. Conventional carburetion systems for small two-stroke engines are designed to provide smooth and stable operation under a variety of speed and load conditions, but give little consideration to fuel consumption or exhaust emissions. The potential advantages of fuel injection in two-stroke engines are two-fold: more precise control of the air-fuel ratio over the entire range of operation, permitting the engine to operate with leaner mixtures; and the possibility of using timed injection and/or in-cylinder injection to eliminate HC emissions due to short-circuiting of fresh charge during scavenging.

The electronic fuel injection systems used in modern automobiles provide a precisely metered amount of fuel, based on a measure of the air flow into the engine. The fuel supply system, which provides the fuel flow to the injection system, consists of a fuel pump, fuel filter and pressure regulator. The fuel injector is a high-speed solenoid valve connecting the pressurized fuel supply to the engine air intake. By opening the valve, the electronic control unit permits pressurized fuel to spray into the air intake, where it mixes with air, vaporizes, and is inducted into the engine.

A similar fuel injection system could be applied in advanced small two-stroke engines. This system could be configured to spray fuel either into the intake port, or into the crankcase, to provide better mixing and increased time for vaporization. Numerous studies have been undertaken with two-stroke engines using this approach to reduce exhaust emissions (Sato et al., 1987; Nuti, M., 1988; Plohberger et al., 1988; Beck et al., 1986; Duret et al., 1988; Huang et al., 1991; Leighton et al., 1994, Yoon et al., 1995).

By appropriate control of fuel injection timing, it is possible to reduce the hydrocarbon content of the air that short-circuits the combustion chamber during scavenging. Because of the need to assure a combustible mixture at the spark plug, however, it would not be possible to eliminate short-circuiting HC completely in port or crankcase-injected engines. Furthermore, some ingenuity is required to provide the pumping power necessary to maintain injection pressure without adding unduly to the size and cost of the engine. In this discussion, we will refer to this approach as "indirect injection".

An alternative fuel injection approach can eliminate short-circuiting entirely. This is to inject the fuel directly into the cylinder near or after the time that the exhaust port closes. This approach is generally referred as direct in-cylinder fuel injection. Because injection directly into the cylinder provides very little time for fuel mixing and vaporization, direct fuel injection systems must inject very quickly, and achieve very fine levels of atomization of the fuel. This type of fuel injection can use high-pressure, liquid-fuel injection systems to inject the fuel directly into the cylinder (Sato et al., 1987; Nuti, M., 1988; Plohberger et al., 1988; Beck et al., 1986; Yoon et al., 1995). Direct in-cylinder fuel injection can also be achieved with low-pressure fuel systems, using air-blast injection (Duret et al., 1988; Huang et al., 1991; Leighton et al., 1994; Yoon et al., 1995). For air-assisted direct-injection systems, an air pump or similar means is required to supply compressed air for the injection system.

The quality of the atomization of a fuel spray is usually measured in terms of the Sauter Mean Diameter (SMD) of the fuel droplets. In order to quickly vaporize the fuel spray, a fuel droplet SMD of 10 to 20 microns is usually required for direct (in-cylinder) fuel injection. For indirect injection, a fuel droplet SMD of 100 microns is quite acceptable, as the fuel will have time to vaporize in the intake port and during the compression stroke.

A good fuel-injection system needs to have the ability to deliver extremely small fuel droplet sizes, to control spray penetration and fuel distribution. It must also mix fuel adequately with all of the available air in the short time available at the high engine speeds typical of two-stroke operation. In addition to fine fuel droplet size, the fuel droplet size distribution must remain much the same throughout the fuel spray to assure minimum coalescence of the droplets towards the end of the spray plume.

Due to the achievements reported for engines using the air-assisted Orbital Combustion Process (OCP) and similar direct-injection approaches, two-stroke engines are presently a major area of automotive research and development. Some prototype two-stroke engines have reached emission levels comparable to good four-stroke engines. However, only limited studies have been carried out on the application of the advanced direct fuel-injection systems in small two-stroke engines such as those in motorcycles and small handheld equipment. A few prototype injection systems for handheld equipment engines are discussed below.

<u>BKM</u> - The BKM project is partly funded by the New York State Energy Research and Development Authority. As of today, BKM has demonstrated a "proof of concept" breadboard prototype chainsaw equipped with its Servojet high pressure, liquid-fuel direct injection system. In its demonstration, the auxiliary parts that are required to run the fuel injection system, such as fuel and oil pumps, electric motors, pressure regulators etc., were not integrated with the chainsaw. The BKM breadboard prototype has been tested at the University of Michigan, with the injection system operated from a standard 120 volt electrical supply. The average emission data with two different injectors and cylinder heads were reported as 30, 1.29, and 94 g/kW-hr and for HC, NOx, and CO emissions, respectively (EPA, 1995), and no PM emission results were reported. The PM emissions is expected to be quite similar to uncontrolled levels, since no special steps were taken to reduce emissions of unburned lubricating oil. The major problems in incorporating the system into a self-contained, portable chainsaw remain to be resolved.

<u>FMS</u> - The FMS project was funded by the Swiss Department of Forestry. A prototype indirect (intake port) fuel injection chainsaw, has been developed and tested at the Swiss Federal National Test Institute. This system used an FMS electronic control unit and Siemens automotive fuel injector. It is claimed that on the GUT cycle, 33% and 85% reductions in HC and CO emissions were achieved, with a 408% increase in Nox emissions. A video provided by the

FMS also documents the laboratory and field testing of the prototype chainsaw. However, similar to the BKM prototype, the system auxiliaries required to run the prototype chainsaw were not integrated or built into the chainsaw, but were powered by a separate car battery.

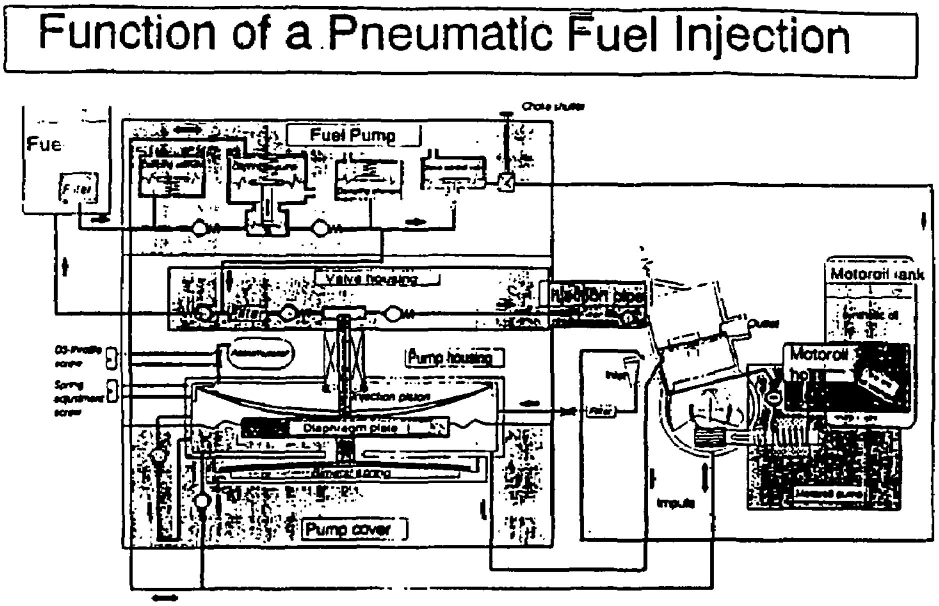

Figure 8: Schematic of the Stihl mechanical direct fuel injection system.

Stihl - Stihl, a major manufacturer of handheld equipment, is developing a prototype mechanical direct fuel injection chainsaw. A schematic of Stihl's mechanical direct fuel injection system is shown in the figure above. For this prototype, all of the components have been integrated into the chainsaw, without auxiliary components such as an external energy supply. As the fuel and lubricating oil are supplied to the engine separately, the prototype chainsaw is equipped with a lubricating oil system, comprising an oil tank, filter, pump, and injection channel. This is different from the current fuel/oil mixing system used in carbureted chainsaws. Similar to the Orbital SEFIS system, the Stihl injection system also uses the pressure pulses of the crankcase to drive the fuel pump. The Stihl fuel injection system does not use any electronic control system, and the injection timing is controlled by a hole in the piston skirt. The emission results for this prototype chainsaw were reported as 20 g/hp-hr for HC emissions, and 200 g/hp-hr of CO emissions. According to a Stihl engineer, a few of these prototype chainsaws have been evaluated in the field, and the results were encouraging. Because of the additional parts, especially costly precision parts, required, the cost of these chainsaws would be significantly higher than for present units. Stihl has estimated that the incremental cost to the customer for these advanced chainsaws would be $200 per unit, even at high production volume.

All these data and studies, as well as data from other studies of fuel-injection systems for automotive two-stroke engines, show that significant reductions in HC and CO emissions can be achieved through the use of fuel-injection systems. However, innovative design will be needed to develop a practical, economical, and efficient fuel injection system that can be installed in a two-stroke engine for handheld equipment.

Skip-firing

Besides precision in fuel metering, another advantage of electronically controlled fuel-injection systems is the ability to shut off fuel injection in some engine cycles. With this feature, the fuel supply can be shut off for a definite number of consecutive engine cycles under idle and light engine load conditions. These are the conditions at which misfire and irregular combustion usually occur. This allows time for exhaust gas to be purged from the combustion chamber, and thus providing better combustion conditions for the next designated engine firing cycle. Thus, irregular combustion under light engine load conditions can be eliminated or minimized.

Researchers at ITRI have successfully applied this skip-injection technique to a scooter engine to minimize unburned HC emissions due to irregular combustion under idle and light load conditions (Huang et al, 1992 & 1993). ITRI researchers found that, without skip-firing, the indicated mean effective pressure (IMEP) varied significantly at idle, and many cycles could easily be identified as having incomplete combustion cycles or even complete misfire. This resulted in a very high concentration of unburned HC emissions: of the magnitude of 3,500 to 4,000 ppm of hexane equivalent in the exhaust. Several skip-injection modes were investigated, including fuel injection every other cycle, and every three, four and five cycles. The results showed that IMEP variations decreased as the number of skipped injections increased. In an engine dynamometer test with fuel injected every four cycles, the HC emissions and fuel flow rate at idle were reduced by 50% and 30% respectively. This skip-injection mode was also applied and tested in a scooter engine, producing the exhaust emissions and fuel economy results shown earlier. Reductions of HC and CO emissions of 58% and 57%, respectively, and a 31% improvement in fuel economy were demonstrated with this approach.

It has been reported that the BKM high pressure fuel injection system for two-stroke engines also uses this approach during idle and low load conditions.

Lubricating Oil Technologies

Lubricating oil is the major source of PM emissions from two-stroke engines. Since the crankcase of a two-stroke engine is used for pumping air or a fuel-air mixture to the combustion chamber, it cannot also act as a lubricant-oil reservoir. Instead, a fine mist of oil is injected into the incoming air stream. As this stream passes through the crankcase, lubrication is provided for cylinder walls, and crankshaft and connecting-rod bearings. Ball or roller bearings are typically used instead of a four-stroke engine's plain bearings. The oil mist continues to the combustion chamber, where some of it is trapped and burned. Oil that is not trapped in the combustion chamber, or which survives the combustion in the chamber, recondenses in the exhaust plume to create the blue or white smoke that is the distinguishing characteristic of the two-stroke engine. Any phosphorus or other deposit-forming additives in the two-stroke oil can also be expected to poison the catalytic converter, reducing its efficiency. Thus, two-stroke oils for catalyst-equipped motorcycles or equipment will need to be formulated without these compounds.

Table II: Comparison of particulate emissions from a two-stroke motorcycle engine lubricated with mineral oil and a low-smoke PIB oil.

Particulate Emissions (g/600 liter Exhaust Gas)			
Fuel Oil Ratio	**20 : 1**	**40 : 1**	**60 : 1**
Conventional Mineral Oil			
Solid Component	0.009	0.005	0.006
Oil Component	0.304	0.247	0.204
Total	0.313	0.252	0.210
Low-Smoke Oil With PIB			
Solid Component	0.008	0.005	0.004
Oil Component	0.228	0.120	0.061
Total	0.236	0.125	0.065

Source: Sugiura et al (1977).

Lubrication system - Three approaches are commonly used to supply lubricating oil to two-stroke engines: pre-mixing with the fuel when it is added to the tank; line-mixing in which the oil is metered into the fuel between the fuel tank and the engine; and oil injection, in which the lubricating oil is metered directly into the intake manifold or other points using a pump controlled by engine speed and/or throttle setting. The last two approaches are common in motorcycle engines, as they have the ability to control the flow rate of the lubricating oil and provide more reliable lubrication. For cost reasons, however, nearly all hand-held equipment engines premix the oil with the fuel. Most chainsaws do have an automatic lube oil feeder, but this is for the chain lubricant, not the engine oil.

The injection-type lubricating oil metering system provides the best control of oil metering. Orbital has designed an electronic lubrication system for their OCP two-stroke engines to reduce the amount of oil required by the engine. Several models of Yamaha two-stroke motorcycles marketed in Asia have also used an electronic lubricating oil metering system to alter the lubricating oil flow to the carburetor according to the engine load demand. The Yamaha Computer-Controlled Lubrication System (YCLS) supplies the required amount of lubricating oil to the engine according to the engine speed, using an electronic control unit and three-way control valve. In a fuel-injected two-stroke engine, this function could be handled by the same electronic control unit as the fuel injection system.

"Low-smoke" oil - Conventional two-stroke lubricating oils are based on long-chain paraffin or naphthene molecules that break down slowly under combustion conditions, and are thus resistant to combustion. The use of synthetic long-chain polyolefin materials instead of naphthenes and paraffins can significantly reduce smoke opacity and particulate emissions from two-stroke engines. Because of the periodic occurrence of double carbon bonds in the polyolefin chain, these chains break down much more rapidly and thus burn more completely in the two-stroke engine. Studies by Souillard (Souillard et al., 1971), Sugiura (Sugiura et al., 1977), Kagaya (Kagaya et al., 1988), and Eberan-Eberhorst (Eberan-Eberhorst et al, 1979) have provided ample evidence that substitution of polyisobutylene (PIB) for bright stock or other heavy lube-oil fractions in two-stroke lubricating oils can reduce engine smoke levels and particulate emissions. An experiment performed by Broun of Lubrizol further demonstrated the decrease in smoke levels using such materials (Broun et al, 1989). Results of lubricity tests by independent laboratories using lubricating oil with PIB and bright stock showed that the lubricity performance for both lubricating oils was essentially the same.

In addition to smoke levels, Sugiura et al.'s study also investigated the effect of PIB on particulate emissions (Sugiura et al., 1977). A comparison of the particulate emissions with a conventional oil and oil with PIB is shown in table II. As this table shows, substantial reductions in particulate emissions were achieved using oil with PIB, ranging from 25 to 70% depending on the fuel/oil ratio. It also shows that the leaner the fuel/oil ratios, the lesser the particulate emissions, especially for the oil with PIB. Thus, higher particulate emission reductions were observed with the oil with PIB at leaner fuel/oil ratio as compared to conventional oil.

While research is still under way to formulate better lubricating oils for two-stroke engines, a "low smoke" polyisobutene based lubricating oil is being required to be used for two-stroke mopeds and motorcycles in some of the countries of Southeast Asia, including Thailand. The current Japanese standard and a proposed International Standards Organization (ISO) standard for two-stroke oil include a special category of low-smoke oils.

Although probably helpful, the use of low-smoke lubricating oils alone will not solve the particulate problem for two-strokes. The oil contained in the 20-30% of the fresh charge that short-circuits the cylinder will be unaffected by combustion. In addition, there is a possibility that the combustion of the polyisobutene lube stock may increase emissions of toxic air contaminants, especially 1,3 butadiene. Further laboratory research is needed to assess the real effects of these oils on particulate and other emissions.

APPENDIX D:

DETERMINING HIGH, INTERMEDIATE, AND LOW VOLUME ENGINE FAMILIES FOR NON-HANDHELD AND HANDHELD ENGINES

Determining the High, Intermediate, and Low-Volume Engine Families for Non-Handheld Engines

We estimated the incremental costs of modifying non-handheld engines for a high, intermediate, and low volume engine family to provide a possible range of incremental costs estimates. These estimates per engine for a high, intermediate, and low volume family correspond to case 1, 2, and 3 of the study of non-handheld engines (Part 1). The volumes were selected as a result of an analysis of the PSR database and were also geared to represent the potential volume size difference between class I and class II engine lines.

The high-volume engine family was based on the largest class I engine lines by the largest class I small engine manufacturers (Briggs and Stratton and Tecumseh). Using 1993 sales information from the PSR database, we identified the models with the largest sales volume for both these manufacturers. In determining the largest sales volume, we accounted for the use of the engine in all applications, as loose engines for a distributor and as exports. We assumed the model was essentially its own engine family. We then averaged the largest model sales for each manufacturer. Specifically, we counted 1,200,000 units for a Briggs and Stratton model 92900/94900 engine. We counted 1,200,000 units for a Tecumseh model TVS90 engine. The average was 1,200,000 units.

An intermediate-volume engine family provided a typical mid-range volume. Because engine family size for the class II market tends to be much smaller than for the class I market, the intermediate-volume could also be used to account for the possibility of that certain engine modifications would be used on class II, but not class I engines. Consequently, for this intermediate-volume number, we examined the high-volume engine families of the largest class II engine manufacturers (Briggs and Stratton and Tecumseh). We focused our search on side-valve engine models because these have the potential to undergo any of the possible engine modifications studied in this report. In determining the largest sales volume, we accounted for the use of the engine in all applications, as loose engines for a distributor and as exports. We then averaged the largest model sales for each class II manufacturer. Specifically, we totalled approximately 300,000 unit for a Briggs and Stratton line and 124,000 units for a Tecumseh line. The average was roughly 200,000.

To determine the low-volume family, we examined the manufacturers that have a small market share of the class I or class II engines. We defined small market share as between 0.2 and 4 percent of the combined class I and class II market. The 0.2 threshold was to eliminate the handful of manufacturers that generated really insignificant market share (e.g., 247 total engines sold from ACME). We examined the high-volume engine lines for these manufacturers and came up with 35,000 based on an examination of both class I and class II engines. By averaging sales data from Kawasaki and Wisc-Teledyn, we determined that the class I and class II models varied between 25,000 and 45,000 units, respectively. Consequently, for the low-volume family, we selected the midpoint or 35,000.

Determining the High and Low Volume Engine Families for Handheld Engines

For the handheld engines, we elected to provide numbers for only a high and low volume family because we were not accounting for the possibility of that certain engine modifications would be used only on certain classes of handheld engines. Also, the range between high and low-volume is less prominent for handheld than non-handheld engines. The incremental cost estimates per engine for a high and low volume family correspond to case 1 and 2 of the study of handheld engines (Part 1).

For the high-volume engine family, we conducted a similar analysis as for the non-handheld engine market. The handheld engine market is largely composed of four engine manufacturers - Poulan, Homelite, Ryobi, and Stihl. Using 1993 sale information from the PSR database, we identified the models with the largest sales volume for all these manufacturers. In determining the largest sales volume, we accounted for the use of the same engine in all applications, as loose engines for a distributor and as exports. We then averaged the largest model sales for each manufacturer. Specifically, we averaged 800,000 units for a Ryobi/Inertia Dynamic model. 400,000 units for a Homelite model, 350,000 units for a Poulan model, and 160,000 units for a Stihl model. The average was approximately 400,000 units for a single model from the manufacturers with the largest market share.

We then conducted a similar analysis of the manufacturers with a small market share. Like for the non-handheld, we defined that small market share as between 0.2 and 4 percent of the combined class III, IV, and V market share. The 0.2 threshold was to eliminate the handful of manufacturers that generated really insignificant market share (e.g., 828 total engines sold from US Engines). The average number of engines for two manufacturers with small market shares - Kioritz (95,000 engines) and Tecumseh (88,000) - was approximately 90,000 engine units.

Determining the Special High-Volume Production for Manufacturing an Improved Carburetor for Non-Handheld Engines (see Section 4.6 of Study)

An improved carburetor, due to an improvement in manufacturing variability, would be used in many models of relatively similar horsepower. Therefore, the annual production of carburetors could be higher than the even 1.2 million engines, representing only one high-volume class I engine line. To determine the special high-volume production number for an improved carburetor, we selected a manufacturer with a large market share (Briggs and Stratton) and added the production volumes for any engine models between 3.5 and 5 horsepower. These models could share the same improved carburetor. The resulting total was 4 million engines which was used in the study. The analysis was performed using the PSR ENGINDATA database.