Chapter 3: Technologies and Standards

3.1. Introduction

The Clean Air Act Amendments of 1990 Section 213(a)(3) present statutory criteria that EPA must evaluate in determining standards for nonroad engines and vehicles which " achieve the greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the engines or vehicles to which such standards apply, giving appropriate consideration to the cost of applying such technology within the period of time available to manufacturers and to noise, energy, and safety factors associated with the application of such technology." This chapter presents the technical analyses and information that form the basis of EPA's determination that the proposed emission standards are technically achievable accounting for all the above constraints except cost. Specific areas of discussion are: a basic description of the technologies examined, current status of the technology in the existing market, new and in-use emission performance of each technology, impact of the engine technology on equipment design and use, and impact of the technology on noise, safety, and energy. Finally, this chapter concludes with a discussion of the proposed standards and how these standards meet the statutory criteria.

3.2. Technologies

Section 3.2. contains emission reduction projections and per engine cost estimates on the several types of technologies the Agency considered during the development of the proposed Phase 2 standards.

3.2.1 Improvements to existing 2-stroke engines

3.2.1.1 Description of 2-stroke Technology -- Spark-ignited two-stroke technology has seen wide spread use in the small engine market, particularly in handheld equipment applications. The basic operating principle of the charge scavenged two-stroke engine (traditional two-stroke) is well understood; in two strokes the engine performs the operations of intake, compression, expansion and exhaust, which the 4-stroke engine requires four strokes to accomplish, additional information on the basic operation of 2- and 4-stroke engines is widely available in the literature, including the references listed at the end of this Chapter.(Ref. 1),(Ref. 2)

3.2.1.2 Current State of Technology Development for 2-stroke Engines -- The majority of existing internal combustion engine powered handheld equipment currently being produced use two-stroke technology. Because of manufacturers many years experience in designing 2-stroke engines and Phase 1 experience, manufacturers will certainly investigate the feasibility of meeting more stringent standards through improvements to Phase 1 designs.

In a report prepared for EPA, Southwest Research Institute (SwRI) conducted a study of several two-stroke engine designs certified to the CARB Tier 1 Utility, Lawn and Garden Engine regulation.(Ref. 3) In this report, SwRI examined several two-stroke engines which were among the lowest

HC+NOx emitting engine certified to CARB at that time. SwRI concluded the following;

- leaner calibration to reduce HC and CO emissions with requisite improved engine cooling
- improved carburetor with more precise intake mixture control
- improved combustion chamber design to promote more complete combustion
- improved transfer port design to reduce scavenging losses and HC emissions
- single point operation calibration optimization
- higher manufacturing quality with reduced assembly tolerances and component variation

SwRI points out that any specific engine family may use a combination of these improvements, but may not utilize all.

3.2.1.3 Exhaust Emission Performance and Cost of 2-stroke Technology

3.2.1.3.1. Uncontrolled and Phase 1 Technology 2-stroke Engines -- As discussed in reference 1 to Chapter 3 (see ICF, 1996, Chapter 6.2), the majority of HC emissions from traditional 2-stroke engines are a result the short circuiting of fresh charge during scavenging and misfire or partial combustion at light loads and idle conditions. In addition, high HC and CO emissions also result from incomplete combustion due to rich air/fuel ratios. NOx emissions from traditional 2-stroke engines tend to be low because of the rich air/fuel ratio and the inherent EGR from imperfect scavenging.

Appendix B contains a list of the Federally certified Phase 1 small engines. As can be seen from Appendix B, many engine families using traditional 2-stroke designs have been certified to the Phase 1 program. The Phase 1 standards for HC and for NOx, if combined into HC+NOx, would be 300, 246, and 166 g/kW-hr for Classes 3, 4, and 5, respectively. As can be seen from Appendix B, many engine families are substantially below the Phase 1 levels, and in fact, several engine families at the new engine level are below the proposed Phase 2 in-use levels.

Information regarding the in-use emission performance of 2-stroke handheld engines is limited. The Agency has collected information on uncontrolled 2-stroke engines collected from actual owners. (Ref. 4),(Ref. 5),(Ref. 6),(Ref. 7) This data indicates 2-stroke technology has the potential to experience high rates of in-use deterioration of HC, on the order of two times the new engine value. Information on in-use emission performance of Phase 1 technology 2-strokes is also limited. In preparation for the Phase 1 regulation, several members of PPEMA ran a test program which included manufacturer controlled field testing of seven Phase 1 technology traditional 2-stroke engines, six were aged to 50 hours, and one out to 225 hours (see Appendix C of the RSD for Phase 1 rule, reference 7 to this Chapter). This data showed relatively low deterioration in HC+NOx emissions, with DF's ranging from slightly less than 1.0 to approximately 1.2 at 50 hours.

3.2.1.3.2. Improvements to Phase 1 Technology 2-stroke Engines-- Manufacturers will likely investigate the improvements discussed in the 1996 SwRI report in order to meet the proposed Phase 2 standards. Based on the SwRI report and the large number of engine families which are already substantially below the Phase 1 standards, the Agency estimates improvements to existing 2-stroke Phase 1 engine families can result in a 30 percent decrease in the in-use HC+NOx emissions of Phase 1 two-stroke technology handheld engines.

The ICF 1996 report contains a discussion of the per engine costs of applying improvements to Phase 1 technology 2-stroke engines (see ICF 1996, ref. 1 to this Chapter). As presented in the ICF 1996 report, per engine costs are effected by engine family production volumes due to the fact that most costs are fixed costs and not variable hardware costs. ICF analyzed costs for engine families based on production volumes of 90,000 units, and 400,000 units. Based on the confidential Phase 1 certification data, the Agency believes these production volumes are appropriate for estimating handheld engine costs. ICF estimated the costs of improvements in scavenging through optimization of piston and port designs, and improvements to combustion chamber designs for 2-stroke engines. The SwRI 1996 report (see reference 3 to this Chapter) identified several additional features which would reduce Phase 1 two-stroke engine HC+NOx emission rates far below the Phase 1 standard, including: improved carburation, and improvements to manufacturing tolerances. The Agency has used the ICF 1996 report estimates for 4-stroke engine improvements to estimate these additional improvements. Table 3-01 presents a summary of the estimated per-engine costs associated with improvements to handheld 2-stroke technology.

TABLE 3-01
Estimated per Engine Costs for Improvements to Handheld 2-stroke Engines

Improvements to Phase 1 2-stroke Engines	Per Engine Costs for Family w/ 90,000 Units Annual Production	Per Engine Costs for Family w/ 400,000 Units Annual Production
Carburetor Improvements*	$0.42	$0.42
Scavenging and Combustion Chamber Improvements	$1.43	$0.34
Manufacturing Tolerance Improvements*	$3.80	$0.72

(* note, for the Carburetor Improvements, the Agency used the estimated cost for the Class 1, 1.2Million/year scenario, and for the Manufacturing Tolerance Improvements, the Agency based the 90,000 unit estimate on the nonhandheld 35,000 unit estimate, and the 400,000 unit estimate is based on the nonhandheld 200,000 estimate)

These estimates indicate that improvements to 2-stroke engines could cost up to a range between $1.48 and $5.65 per engine, depending on the improvements required and the annual production volumes.

3.2.1.4 Impact on Equipment Design and Use of 2-stroke Technology -- The majority of the changes the Agency would expect to see from improvements to existing 2-stroke designs would have no negative impact on equipment design and use. The expected changes include improved carburation, improved combustion chamber design, improved transfer port design, and higher manufacturing quality, these changes would have no negative impacts on equipment design. The only exception to this is the use of leaner air-fuel mixture calibrations. Leaner air-fuel mixtures will reduce HC emissions, but it may increase exhaust gas temperature. Depending on the current operating characteristics of the engine, manufacturers may need to reduce the exhaust gas temperature, this will likely be done by making enhancements to existing muffler designs, and may result in increased muffler size, however, this will have little if any impact on the equipment use.

3.2.1.5 Technology Impact on Noise, Safety, and Energy from 2-Stroke Technology -- The Agency would expect no negative impacts on noise from improvements to existing 2-stroke engine designs. Chapter 8.2 of Blair, 1993 (<u>see</u> Ref. 2 to this Chapter) describes the two most significant sources of noise from a two-stroke engine as: (i)induction pressure pulses generated by the intake system, and (ii) pressure pulses generated by the exhaust gas at the exhaust port. The Agency does not expect significant changes in intake designs to improve the exhaust emissions of Phase 1 technology engines, if anything, improvements to intake air filters may be made to improve in-use durability, and this would tend to absorb induction pressure pulses and reduce noise levels. Changes in exhaust port designs would almost certainly be part of a manufacturers strategy to lower emissions, however, the impact on noise generation is expected to be minimal. One 2-stroke handheld engine manufacturer indicated that changes in intake/transfer/exhaust port designs to lower scavenging losses and reduce emissions to meet the Phase 1 standards have made no discernable difference in engine noise, nor would changes to meet lower emission levels be expected to change noise levels.(Ref. 8)

The Agency would expect no negative impacts on the safety of handheld equipment from improvements to existing 2-stroke designs. The U.S. Forest Service has developed maximum exhaust gas temperature and surface temperature requirements for equipment used on Federal land. However, the

Agency expects only small changes in exhaust gas and muffler skin temperature would result from engines designed to meet the proposed standards, and any increase in temperature could be compensated for with modifications to muffler designs. As discussed in Section 3.2.1.3, several 2-stroke engine families have been certified to levels significantly below the Phase 1 standards, and those engine families continue to comply with existing U.S. Forest Service requirements.

The Agency would expect improvements to existing 2-stroke designs to result in significant fuel economy improvements for many 2-stroke engine families. Phase 1 technology two-stroke engines operate at air-fuel ratio's which are richer than stoichometery, as these engines are enleaned to reduce emissions, fuel economy will improve.(Ref. 9) The Agency would expect the largest improvement in fuel economy to come from reductions in scavenging losses. Improvements in intake/transfer/exhaust port designs which reduce scavenging losses would result in lower fuel consumption. Based on limited test data the Agency estimates that improvements to existing 2-strokes would result in approximately a 6 to 17 percent reduction in fuel consumption, depending on the engine Class. Section 4.6.1.2 of this draft RSD contains additional information on estimated 2-stroke fuel consumption.

3.2.2 Application of Catalytic Convertors to Handheld Engines

3.2.2.1 Description of Catalyst Technology -- Catalytic convertors are add-on devices used to lower exhaust emissions from engines after they exit the combustion chamber. Typically, a catalyst consists of a ceramic or metallic support (often called the substrate), that is coated with a wash-coat which contains catalytic material (typically a rare-earth element such as platinum, rhodium and/or palladium). The catalytic material initiates a chemical reaction which can oxidize hydrocarbons and carbon monoxide, and it can reduce oxides of nitrogen.

Additional information regarding the fundamentals of catalytic convertors, and information specific to catalyst and small engines can be found in “Report - Exhaust Systems Subgroup of the Technology Task Group”, a report published by a task group established during the Regulatory Negotiation for Small Engine Phase 2 Rulemaking.(Ref. 10)

3.2.2.2 Current State of Catalyst Technology Development -- Historical data indicates that catalysts have seen limited use on small engines in the U.S. Prior to EPA or CARB small engine regulations catalyst were used in limited numbers on some types of indoor equipment, such as indoor propane fueled floor buffers (also called floor burnishers), but no handheld applications utilized catalyst technology.

Federal certification information shows that one manufacturer, Husquvarna, has certified three engine families using 2-stroke technology with a catalyst. These Husquvarna families have been developed for string trimmer/brush cutter applications.

The Agency believes many manufacturers have investigated catalyst technology for small engines from a research perspective. However, the majority of small engine manufacturers have little or no experience in the production of catalyst equipped small engines.

3.2.2.3 Exhaust Emission Performance and Costs of Catalysts -- Reference 10 to this Chapter (“Report - Exhaust Systems Subgroup of the Technology Task Group”) contains a summary of new engine data on the HC and NOx reduction potential from the application of catalyst to 2- and 4-stroke small engines. The majority of these engines were uncontrolled or Phase 1 technology gasoline engines with prototype catalyst added on. The application of catalysts to these small gasoline 4-stroke engines showed reductions in new engine HC emissions 40 to 80 percent and NOx emissions were reduced 20 to 80 percent for some engines, however, it some cases NOx emissions increased 25 to 50 percent. Information presented in reference 10 to this Chapter on 2-stroke engines with catalysts showed a 20 to 80 percent reduction in HC, and a 10-20 percent reduction in NOx for some engines, however, NOx increased up to 40 percent for other engines. Based on this information, the Agency estimates that catalyst technology has the potential to reduce new engine HC+NOx emissions from 4-stroke and 2-stroke engines by 20 to 80 percent from uncontrolled and Phase 1 technology.

Husqvarna has certified three engine families to the Phase 1 rule which utilize catalyst on a two-stroke engine, the engine is intended for use in a sting trimmer application. Agency testing of one of these engines showed new engine HC+NOx emissions of approximately 90 g/kW-hr. Husqvarna has indicated in press release material that this engine combines improved scavenging for lower engine out emissions along with a low efficiency catalyst to reduce HC+NOx emissions. Information on the catalyst efficiency for this engine is not publicly available.

Information on the in-use emission performance of catalyst equipped small engines is very limited. The reductions in HC and NOx described above are reductions in the new engine emission rates of small engines. The Agency's experience with on-highway catalyst technology has shown that catalysts are susceptible to degradation in-use. The in-use performance of catalysts can degrade from several mechanisms, including the physical deterioration of the substrate from mechanical shock, vibration, and extreme temperatures, and the deactivation of the catalyst material from chemical poisoning (such as sulfur). The Agency is concerned that in-use deterioration of small engine catalysts will occur, but the extent of the potential problem is unknown. Without information regarding the in-use performance of catalyst equipped engines, it is difficult to estimate the emission reduction potential of catalyst technology on small engines.

In the ICF 1996 report (see reference 1 to this Chapter), the costs of applying catalyst to a 2-stroke engine was estimated. The Agency estimates the addition of a catalyst to a 4-stroke engine would be similar, particularly for the engineering research and development work. However, the cost of the catalyst itself would likely be higher for a nonhandheld 4-stroke engine in order to handle the increased exhaust gas flow rate from the larger nonhandheld engines.

ICF considered the costs for both a metallic substrate and for a ceramic substrate, with the estimated cost of a metallic substrate being substantially more. Table 3-02 is a summary of the cost information contained in the ICF 1996 report for catalyst and 2-stroke engines.

TABLE 3-02
Summary of per Engine Cost for Application of a Catalyst to a Handheld 2-stroke Engine (data from ICF, 1996)

Cost Item	Engine Family Annual Production = 90,000, ceramic substrate	Engine Family Annual Production = 90,000, metallic substrate	Engine Family Annual Production = 400,000, ceramic substrate	Engine Family Annual Production = 400,000, metallic substrate
Catalyst	$4.00	$8.00	$4.00	$8.00
Catalyst Assembly Labor	$0.58	$0.58	$0.58	$0.58
Catalyst Fixed Cost	$1.20	$1.20	$0.30	$0.30
Muffler/ Heat Shield Hardware Cost	$0.90	$0.90	$0.90	$0.90
Muffler/ Heat Shield Fixed Costs	$0.98	$0.98	$0.24	$0.24
Total	**$7.66**	**$11.66**	**$6.02**	**$10.02**

Table 3-02 shows that the cost of adding a catalyst to a 2-stroke engine is estimated to be between $6.02 and $11.66 per engine, depending on the type of catalyst and the engine family annual production. The costs shown in Table 3-02 only account for the cost of adding a catalyst to an Phase 1 technology 2-stroke engine, not for internal improvements to the engine. Internal engine improvements are necessary in order to lower engine out emissions and increase engine out in-use durability prior to the application of a catalyst. As discussed in Section 3.2.1.3, internal engine improvements could cost an additional $1.48 to $5.65 per engine, depending on the improvements required and the engine family annual production volume. Combining the cost of adding a catalyst with the cost of internal improvements to a Phase 1 technology handheld 2-stroke engine results in a potential increase between $7.50 and $17.31 per engine.

3.2.2.5 Impact on Equipment Design and Use of Catalyst -- The use of catalyst would effect the muffler design of small engines. Mufflers would need redesigns in order to house the convertor, as well as additional heat shielding or other safety shields to protect the user from excessive muffler skin temperature. In addition, the muffler design may need to be modified in order to accommodate increased exhaust gas temperature.

The addition of a catalyst would also add weight to the engine, however, the added weight would likely be negligible compared to the dry weight of the engine.

3.2.2.6 Catalyst Technology Impact on Noise, Safety, and Energy -- The Agency would expect little impact on engine noise from the application of catalyst to small engines. If any impact on noise did occur, it is likely the catalyst plus a redesigned muffler would act to lower the noise generated by an engine, since the catalyst would absorb and not generate sound.

Engine manufacturers have raised concerns regarding the safety of catalyst on small engines. The principle concerns relate to increases in muffler skin temperature and exhaust gas temperature from the use of catalyst. The U.S. Forest Service has developed maximum exhaust gas temperature and surface temperature requirements for equipment used on Federal land. In order to continue to meet the requirements of the U.S. Forest Service, manufacturers may need to limit the conversion efficiency of the catalyst in order to maintain a comfortable margin of safety below the Forest Service requirements, and/or redesign the muffler system to enhance the heat shielding of the muffler. As previously discussed, at least Husquvarna has certified three engine families which utilize a catalyst and continue to meet all applicable U.S. Forest Service requirements.

The addition of a catalyst would have no significant impact on the energy consumption of an engine. Catalyst are add-on devices which would have minimal, if any, impact on the engine's air/fuel ratio or power output, therefore, no change in fuel consumption would be anticipated.

3.2.3 Conversion of Handheld 2-stroke designs to 4-stroke designs

3.2.3.1 Description of 4-stroke Handheld Engine Technology -- As discussed in Section 3.2.1.1, gasoline powered handheld equipment have traditionally used charge scavenged 2-stroke engines as a power source. Two-stroke engines have several advantages over 4-stroke designs for use in handheld equipment: high power-to-weight ratios; multi-positional operation; and lower manufacturing costs. However, 4-stroke engines have lower HC exhaust emissions and better fuel economy than 2-stroke designs. Additional information on the design and performance differences between 2- and 4-stroke engines is widely available in the literature, see for example references 2 (Blair, 1990) and 9 (Taylor, 1985) of this Chapter.

3.2.3.2 Current State of 4-stroke Handheld Engine Technology Development -- The majority of handheld equipment sold in the U.S. are powered by traditional 2-stroke engines. In recent years one handheld engine/equipment manufacturer, Ryobi, has introduced a 4-stroke powered string-trimmer into the U.S. market place. In addition, America Honda recently announced they will introduce a 4-stroke power unit for use in handheld application, with two displacements to be offered in the Class IV displacement (20-50cc). However, for the majority of handheld engine manufacturers, 2-stroke designs represent their entire handheld product line. Prior to the introduction of the Ryobi 4-stroke engine, 100 percent of handheld equipment were powered by 2-stroke engines. Therefore, though the design principles of 4-stroke technology are well known, the majority of handheld engine manufacturers have little experience in producing 4-stroke engines.

3.2.3.3 Exhaust Emission Performance and Costs of 4-stroke Handheld Engine Technology -- Prior to the introduction of the Ryobi 4-stroke handheld engine in the early 1990's, no handheld 4-stroke engines existed, therefore, no exhaust emission data on uncontrolled engines is available. Federal certification data for the Ryobi engine shows the new engine HC+NOx emission rate is 37.6 g/kW-hr, which is 84 percent below the combined Phase 1 Class IV HC and NOx standards. American Honda recommended in their written comments a in-use HC+NOx standard of 72.4g/kW-hr for 4-stroke OHV engines less than 75cc in displacement.(Ref. 11) The level recommended by American Honda is 70 percent below the combined Phase 1 Class IV HC and NOx new engine standards.

In-use emission performance data on handheld 4-stroke engines is not available. However, the Agency would expect the in-use performance of small handheld 4-strokes to be similar to the smaller displacement Class 1 engines. Both the Ryobi and American Honda handheld 4-stroke engines utilize OHV technology. As discussed in Section 3.2.3.3 at 66 hours of use, the Phase 1

Class 1 OHV engines HC+NOx deterioration rate is approximately 1.4 times the new engine value. However, the Class 1 engines are significantly larger in displacement than a handheld engine. For example, a typical Class 1 OHV engine has a displacement of 200cc, while a Class IV handheld engine has a displacement between 20 and 50cc. American Honda has indicated they would expect a small displacement handheld 4-stroke engine to deteriorate at a higher rate than a Class 1 OHV 4-stroke engine.(Ref. 12) Small displacement handheld engines would have higher surface-to-volume ratios than a larger displacement Class 1 engine, and high surface-to-volume ratio's have been correlated with higher HC emissions (see ref. 15 to this Chapter, Patterson, 1972), which may lead to increased combustion chamber deposits and therefore higher in-use deterioration. Based on considerations of higher surface to volume ratio for a handheld 4-stroke engine, the Agency agree's with American Honda's belief that a small displacement 4-stroke engine would likely have higher HC+NOx deterioration than a larger 4-stroke engines, such as a Class 1 engine. Though actual in-use emission data is not available on a handheld 4-stroke engine, the Agency estimates the HC+NOx deterioration factor is likely between 1.5 and 2.0 at 50 hours of use. Multiplying the HC+NOx deterioration factor range of 1.5 to 2.0 with Phase 1 certification value for the Ryobi 4-stroke engine (37.6 g/kW-hr) results in an estimated in-use value between 56.4 and 75.2 g/kW-hr, which is between 70 and 77 percent below the combined Phase 1 Class IV new engine Class IV HC and NOx standards.

The costs of converting handheld 2-stroke to 4-stroke technology was estimated by ICF in their 1996 report (see reference 1 to this Chapter). ICF included as part of their cost analysis a tear down and comparison of a Ryobi 2-

stroke engine and the Ryobi 4-stroke handheld engine. ICF estimated costs for two annual production sizes, 90,000 and 400,000 units per year, which they estimated as typical for the handheld industry. The Agency believes ICF overestimated the labor time associated with those pieces the manufacturer would produce in-house, the Agency believed it is likely that many pieces are manufactured at a time. ICF estimated the following times for each of the following components; 0.5 min. for valve cover, 0.5 min for rocker arm, 1.5 min. for push rod, 0.5 min. for push rod guide, 0.5 min for rocker arm box, 0.5 min for oil pan, 0.5 min. for cam bracket, 0.5 min. for cam follower, 0.5 min. for cam gear, 0.5 min for crank gear, and 3 minutes for cylinder head & cylinder, the Agency revised these estimates downward to the following values, all 0.5 min. reduced to 0.1 min., all 1.5 min. reduced to 0.15 min., and 3 min. reduced to 0.5 min. This resulted in lowering the ICF estimated per engine total parts cost from $8.88 to $4.48. Table 3-03 is a summary of the cost information contained in the ICF 1996 report for conversion of handheld 2-stroke engines to 4-stroke, as modified by the Agency as noted above.

TABLE 3-03
Summary of per Engine Cost for Conversion of
Handheld 2-stroke Technology to 4-stroke Technology (data from ICF, 1996)

Cost Item	Engine Family Annual Production = 90,000	Engine Family Annual Production = 400,000
Additional Parts Estimate	$4.48	$4.48
Additional Labor + Overhead	$1.05	$1.05
Fixed Costs	$4.09	$1.73
Total	**$9.62**	**$7.26**

Table 3-03 shows that the cost of converting a handheld engine family from 2-stroke to 4-stroke engine family is estimated to be between $7.26 and $9.62 per engine, depending on the engine family annual production. It should be noted that this cost estimate was partially based on a tear-down inspection of the Ryobi engine, as of September 1997 the American Honda handheld 4-stroke was not available for inspection, therefore the cost estimates may not be representative of the American Honda design.

3.2.3.4 Impact on Equipment Design and Use of 4-stroke Handheld Engine Technology -- For many types of equipment, the conversion of 2-stroke to 4-stroke technology would have little impact on the design of handheld equipment. Both Ryobi and American Honda have successfully demonstrated a 4-stroke engine can be used in a string trimmer/brush cutter application. In addition, American Honda's claims their engine design is completely multi-positional, which is necessary for many types of handheld equipment, such as chainsaws.

A conversion to 4-stroke designs would likely influence the use of handheld equipment. Consumers would no longer need to pre-mix fuel with 2-stroke oil, but consumers would need to maintain crankcase oil levels at an acceptable level, and perform periodic oil changes.

In many applications, such as lower power residential string trimmers, brush cutters, edgers, blowers, portable generators, and portable pumps, the lower power-to-weight ratios of 4-stroke engines would not be noticeable to consumers. The Agency has heard from handheld engine manufacturers that for engines in the fractional to approximately 1.5kW range, residential users typically do not use the full power rating of the engines to perform the intended work. Therefore, the Agency believes 4-stroke designs could be competitive from a performance perspective with 2-stroke designs.

However, in larger displacement, higher power engines, the power-to-weight disadvantage of the 4-stroke engine would become noticeable, and would likely impact the user through fatigue from the added weight of the engine, and potentially limiting the functionality of the equipment. For example, high powered commercial chainsaws in the Class V category (displacement >50cc) are typically designed for maximum power per cubic centimeter of displacement. In these categories, the 4-stroke engine would likely present a performance problem for users.

3.2.3.5 Impact on Noise, Safety, and Energy of 2-stroke to 4-stroke Conversion -- The Agency expects the conversion of 2-stroke to 4-stroke designs would lower the noise levels from handheld equipment. Two-stroke designs are well known for their relatively high noise levels as compared to 4-stroke engines. As discussed in Section 3.2.1.5, a large source of noise from 2-stroke designs comes from pressure pulses generated by the exhaust gas at the exhaust port. These pressure pulses tend to be higher in a 2-stroke design compared to 4-stroke engines because the 2-stroke engine requires the higher cylinder pressure to begin the blow-down process (see Chapter 2 “Engine Fundamentals”, Patterson, 1972, ref. 15 to this Chapter).

The Agency would expect no change in the safety for the majority of handheld equipment from the conversion of 2-stroke to 4-stroke designs. As discussed in Section 3.2.3.4, the overall design and use of handheld equipment would not change from the conversion to 4-stroke engines, so no change is expected with regards to safety. In addition, the Ryobi 4-stoke handheld equipment has been available for several years, and the Agency is not aware of any safety problems which have occurred from this equipment which can be attributed to the engine type. However, as discussed in Section 3.2.3.4, the Agency is concerned about the potential safety impact from the conversion of large displacement handheld engines, such as Class V chainsaws, which would result from the potential increase in engine weight from the conversion to 4-stroke designs. The Agency request additional information on this topic.

The Agency would expect significant improvements in the fuel economy from the conversion of 2-stroke to 4-stroke designs. The loss of fuel from the scavenging process for 2-stroke engines results in poor fuel economy which the 4-stroke design does not experience. As discussed in Section 4.6.1.2 “Fuel Savings and Impact on Performance - Handheld Engines”, of this draft RSD(Cheryl’s RSD subchapter on fuel savings), based on fuel economy data of Phase 1 technology 2-strokes and the Ryobi 4-stroke engine, the Agency would expect a 6 to 16 percent improvement in fuel economy from the conversion of 2-stroke to 4-stroke designs.

3.2.4 Improvements to Existing 4-Stroke side-Valve Engines

The information presented in this section is relevant for the discussion of nonhandheld (Class I and II) engine technologies.

3.2.4.1 Description of 4-stroke Technology -- Four stroke Otto-cycle side-valve (SV) engines utilize four distinct strokes to complete a combustion cycle, i.e., intake, compression, expansion, exhaust, as compared to the 2-stroke cycle described in section 3.2.1.1. Additional information regarding the 4-stroke Otto-cycle can be found in ICF, 1996 (see reference 1 of this Chapter). In a SV 4-stroke Otto-cycle engine, the intake and exhaust valves are located to one side of the combustion chamber, with the valve stems located below the combustion chamber. In order to accommodate the location of the intake and exhaust valve, the combustion chamber is relatively long and flat, as compared to a 4-stroke over-head valve design (see Section 3.2.5, "Improvements to Existing 4-stroke OHV Engines"). In many cases Phase 1 technology SV engines have the potential for additional emission reductions beyond the Phase 1 levels.

3.2.4.2 Current State of Technology Development for SV Technology -- SV technology has been used for many years in the nonhandheld market place. Historical sales data available from Power Systems Research(Ref. 13) indicates SV engines have represented the majority of Class I and Class II engine sales for at least the past 20 years, so manufacturers are very familiar with SV technology. In addition, to comply with the Phase 1 standards manufacturers likely researched several of the improvements discussed in this draft RSD, though not all of these improvements may have been incorporated to meet the Phase 1 standards.

3.2.4.3 Exhaust Emission Performance and Costs for SV

Technology

3.2.4.3.1. Uncontrolled and Phase 1 Technology SV Engines

Engines -- The Agency presented information on uncontrolled SV Class I and Class II emission rates during the development of the Phase 1 rule (see the RSD for the Phase 1 rule, ref. 7 to this Chapter). The Agency estimated the new engine HC+NOx emissions for uncontrolled Class I and Class II SV engines to be 55 g/kW-hr and 16 g/kW-hr respectively. The Phase 1 HC+NOx standards for Class I and II engines is 16.1 and 13.4 g/kW-hr respectively. The Phase 1 rule resulted in an average reduction in the new engine HC+NOx exhaust emissions value of 70% for Class I SV and 16% for Class II SV from uncontrolled levels.

Information on the in-use deterioration of uncontrolled SV engines is somewhat limited, however, the Agency estimated at the time of the Phase 1 rule that HC emissions increased by a factor of 2.1 and NOx decreased by approximately 60 percent during the lifetime of an engine (see the RSD for the Phase 1 rule, ref. 7 to this Chapter). Much more data is available on Phase 1 SV technology in-use emission performance. In 1996, the Agency received information from several engine manufacturers regarding the in-use performance of Phase 1 technology Class I and II engines, both SV and OHV designs. This in-use manufacturer controlled field data was collected by several manufacturers who hired an independent contractor, Air Improvement Resources (AIR), to evaluate the data.(Ref. 14) AIR analyzed deterioration information from 39 Class I SV engines and 25 Class II SV engines. These engines were aged to a range of in-use hours, between 20 and 300 hours for the Class I engines, and between 110 and 450 hours for the majority of Class II SV engines (two Class II SV engines exceeded 1,000 hours of use). AIR analyzed the HC+NOx deterioration data from these engines, along with data from new engine quality audit data, manufacturer sales information, and individual engine manufacturers engineering judgement. As reported by AIR, they determined the best fit to the deterioration data was of the form;

$$HC + NOx\ Deterioration\ Factor = 1 + CONSTANT \times \sqrt{Engine\ Hours}$$

AIR's results indicate that at 66 hours of use, the HC+NOx deterioration factor (DF) for a Phase 1 Class I SV engine is 1.9, and for a Phase 1 Class II SV engine at 250 hours of use, the HC+NOx DF is 1.6. Multiplying these DF's times the Phase 1 standards result in a conservative estimate of the in-use emission rate of Phase 1 SV engines. The Class I SV estimate at 66 hours is 1.9 * 16.1 g/kW-hr = 30.6gr/kW-hr, and for Class II SV engines at 250 hours, 1.6*13.4 g/kW-hr= 21.4 gr/kW-hr.

The Agency analyzed a subset of the data examined by AIR, namely, the field tested engine data. EPA performed an ordinary least square analysis of HC+NOx deterioration factor (DF) versus usage in hours for the square root of hours function shown above. The Agency's results predict that at 66 hours, the Class I SV HC+NOx DF is 1.9, and for Class II SV at 250 hours 1.6. The Agency's analysis produced very similar results to the AIR analysis. Based on discussions with several of the engine manufacturers who provided test data to AIR, the Agency believes that the majority of the field aged engines used in this study would be considered typical of residential application engines, i.e., engines which are designed for relatively low useful lives.

3.2.4.3.2. Improvements to Phase 1 Technology SV Engines -- The Agency considered a variety of improvements to Phase 1 SV engines in developing the Phase 2 proposal which would reduce HC+NOx emissions. Based on information contained in a Agency contract performed by ICF Inc. (see ICF, 1996 report, ref. 1 of this Chapter) , and a contract performed by Southwest Research Institute (see SwRI, 1996 report, ref. 3 of this Chapter), several types of improvements were considered, a summary of which are presented here.

In some cases improvements in carburation may allow for leaner air/fuel calibrations, which can reduce HC+NOx emissions (see SwRI, 1996 report, Chapter 6 and ICF, 1996 report, Chapter 2.4). However, there are several limitations to this for SV technology. First, the flat shape of the SV combustion chamber, necessary for the location of the intake and exhaust valves, leads to higher surface-to-volume ratio's, which results in lean burn limit which is richer than the lean burn limit a similarly designed OHV engine would experience. As an engine approaches the lean burn limit stable combustion becomes compromised, and once the lean-burn limit is reached combustion is no longer stable and engine performance is negatively effected. Second, lean conditions also can result in poor response to load pick-up, i.e., when an engine is running lean under a stable load, and a quick increase in load occurs, lean conditions can result in engine stumble or stalls, this can be overcome with enrichment devices such as accelerator pumps, but this comes at an increase in cost and complexity. Based on the range of emission values seen from Phase 1 technology SV engines, the Agency believes many SV engine families can see additional improvements to HC+NOx performance from improvements to carburation, though these improvements may be small.

The Agency also considered improvements in combustion chamber design for SV engines. The SwRI 1996 and ICF 1996 reports concluded that improvements to SV combustion chamber design is one method for improving

SV emissions (see SwRI 1996, Chapter 6, and ICF 1996, Chapter 4.1). Traditional small engine SV combustion chambers suffer from high surface-to-volume ratios and dead spaces which result in high HC emissions (see Patterson, 1972, Chapter 5). Redesign of combustion chambers for improved mixing and lower crevice spaces can result in lower HC emissions and the ability to operate at leaner air-fuel ratios.

Another improvement considered for SV technology is improvements to valve seat material. Improvements in valve seat material can reduce in-use distortion of the seat. Valve-seat distortion and poor valve seating can lead to increased exhaust emissions.(Ref. 15)

Improvements in piston ring design were also considered for SV technology. Redesign of the oil control rings can reduce oil consumption in many SV designs (see SwRI, 1996 report, Chapter 6, and ICF 1996 report, Chapter 4.4). Poor oil control can lead to increases in combustion chamber oil deposits which will result in increased in-use emissions.(Ref. 16) The addition of valve stem seals, also called valve stem bushings, is another improvement to SV engines which would reduce combustion chamber deposits and valve deposits. Without valve stem seals, oil mist from the crankcase can leak past the valve stems and create valve and combustion chamber deposits, which will increase in-use emissions. Though most, if not all, Class II SV engines already have valve stem seals, many low cost Class I SV engines may not have incorporated valve stem seals in order to reduce costs (see SwRI 1996 report, Chapter 6, and ICF 1996 report, Chapter 4.4). The addition of valve stem seals to Class I SV engines would reduce in-use emission deterioration.

Improvements in spark ignition and timing can also lead to lower HC+NOx emissions. In the past, manufacturers have likely optimized ignition timing for maximum power, however, ignition timing can be optimized for emissions, with a slight penalty in power and fuel economy (see Chapter 5, Patterson, 1972, ref. 16 of this Chapter). It is likely that many Phase 1 designs have already incorporated improvements in ignition systems optimized for emissions. However, small changes may be feasible, in particular for those Phase 1 designs which have not optimized ignition systems for emissions.

Improvements in valve timing and cam design may be effective in reducing in-use deterioration on some SV engine families. As discussed in the ICF 1996 report (Chapter 4.3), these improvements could result in improvements to the in-use stability of valve timing through improvements in materials.

Finally, the Agency considered the improvements which could be made from reducing manufacturing variability. Manufacturing variability can result in a large variation in new engine emission rates, and loose tolerances on key engine components can result in increased wear and in-use deterioration (see SwRI 1996 report, Chapter 6, and ICF 1996 report, Chapter 4.5)

The ICF 1996 report contains a detailed discussion of the per engine costs of applying these improvements to Phase 1 technology Class I and II SV (see ICF 1996, Chapter 4). As presented in the ICF 1996 report, per engine costs are effected by engine family production volumes. ICF analyzed costs for engine families based on production volumes of 35,000 units, 200,000 units and 2,000,000 units for nonhandheld engines. Based on the confidential Phase 1 certification data, the Agency believes production volumes of 200,000 units and 1,200,000 units are appropriate for Class I SV engines, and production volumes of 35,000 units and 200,000 units are appropriate for Class II SV engine cost calculations. Table 3-04 presents a summary of the per-engine costs associated with improvements to nonhandheld SV technology.

TABLE 3-04

Estimated per Engine Costs for Improvements to Class I and Class II SV Engines

Improvements to Phase 1 SV Engines	Per Engine Costs for Family w/ 35,000 Units Annual Production (Class II only)	Per Engine Costs for Family w/ 200,000 Units Annual Production (Class I&II)	Per Engine Costs for Family w/ 1,200,000 Units Annual Production (Class I only)
Carburetor Improvements*	$8.22	$1.73	$0.49
Combustion Chamber Improvements	$2.06	$0.36	$0.07
Spark Timing Improvements	$0.72	$0.13	$0.02
Valve Timing Improvements	$2.27	$0.51	$0.12
Piston, Piston Ring, Valve Seat Improvements	$4.97	$3.12	$2.80
Manufacturing Tolerance Improvements	$2.25	$0.73	$0.46

(* note, for the Carburetor Improvements, ICF assumed a volume of 4 million carburetors, the Agency believes this is overly optimistic, therefore, the costs were calculated based on the engine family volumes)

Based on this information, the Agency estimates improvements to Class I SV engines would cost up to between $3.96 and $6.58 per engine, and improvements to Class II SV engines could cost up to between $6.58 and

$20.49 per engine, depending on the improvements required and the engine family annual production volume.

The Agency expects that these improvements to Phase 1 Class I and Class II SV engines would result in a 10 to 20 percent reduction in the in-use HC+NOx exhaust emissions. Using the Phase 1 HC+NOx standard as the new engine value results in a Phase 1 in-use estimates of 30.6 g/kW-hr HC+NOx for Class I engines and 21.4 g/kW-hr HC+NOx for Class II engines. However, this ignores the fact that Phase 1 SV engine families on a sales weighted average are certified approximately 15% below the Phase 1 standards. A 10 to 20 percent improvements to the actual certified Phase 1 SV engines, combined with a compliance margin of 10 percent, results in an estimated HC+NOx in-use level between 22.9 and 26.0 g/kW-hr for Class I SV engines, and an estimated HC+NOx in-use level between 14.6 and 16.0 g/kW-hr for Class I SV engines.

3.2.4.4 Impact on Equipment Design and Use from Improvements to SV Technology -- As discussed previously, SV technology is well known in the nonhandheld market, where it has been used for decades. The improvements to SV technology described in this section would have no negative impacts on nonhandheld equipment design and use. Most of the improvements discussed are internal to the engine and would not effect the overall shape or functionality of the engine with respect to it's use in a piece of equipment.

3.2.4.5 Impact on Noise, Safety, and Energy from Improvements to SV Technology-- The improvements to Phase 1 technology engines discussed in this section would have little, if any, negative impact on the noise and safety of these engines or the equipment they are designed to be used in. The improvements discussed; carburation, combustion chamber designs, spark timing, valve timing, oil control, and manufacturing tolerances, would reduce in-use emissions, but appear to have little relevance to noise or safety.

The Agency would expect that improvements to engine combustion chamber design and improvements to carburation may result in leaner engine air-fuel calibrations, which would result in improvements to fuel economy. However, as discussed in Section 3.3.3.4, enleanment of Phase 1 SV engines would be limited. The Agency estimates these changes would be marginal and represent no significant improvement in fuel economy.

3.2.5 Improvements to Existing 4-stroke Over-head Valve Engines

3.2.5.1 Description of 4-stroke Over-head Valve Technology -- Four-stroke over-head valve (OHV) engine designs have intake and exhaust valves located above the cylinder head and combustion chamber, rather than to the side of the cylinder head as in SV engine designs. Additional information describing the design details of 4-stroke OHV, as well as 4-stroke SV and 2-stroke engines is available in ICF 1996 (ref. 1 to this Chapter).

3.2.5.2 Current State of Development for OHV Technology -- OHV engine designs have been manufactured and sold for use in nonhandheld applications for many years. According to sales information available from Power Systems Research (see ref. 13 to this Chapter), OHV engines represented less than 1 percent of Class I engine sales prior to 1986, but since that time they have grown to represent between 10 and 15 percent of total U.S. sales for the past eight years. In the 1970's and 1980's, Class II engines were predominantly SV technology. Beginning in 1985, OHV engines have steadily increased as a percentage of Class II sales, averaging approximately a 3 percent increase per year; by 1995 OHV engines represented approximately 35 percent of Class II engine sales. Manufacturers have had many years experience in designing and producing OHV technology.

3.2.5.3 Exhaust Emission Performance and Costs of OHV Technology --

3.2.5.3.1. Uncontrolled and Phase 1 Technology OHV Engines-- During the development of the Phase 1 regulation the Agency had little information regarding the in-use HC and NOx exhaust emission performance of OHV technology, and in fact, most of the Agency's assumptions regarding OHV deterioration were based on data from SV technology (see ref. 7 to this Chapter, RSD for the Phase 1 rule).

As discussed in Section 3.2.4.3, in 1996, the Agency received information from several engine manufacturers regarding the in-use performance of Phase 1 technology Class I and II engines, both SV and OHV designs (see ref. 14 to this Chapter). Air Improvement Resources (AIR) analyzed deterioration information from 12 Class I OHV engines and 35 Class II OHV engines. These engines were aged to a range of in-use hours, between 120 and 300 hours for the Class I OHV engines, and between 180 and 475 hours for the Class II OHV engines. AIR analyzed the HC+NOx deterioration data from these engines, along with data from new engine quality audit data, manufacturer sales information, and individual engine manufacturers engineering judgement. As reported by AIR, they determined the best fit to the deterioration data was of the form;

$$HC + NOx\ Deterioration\ Factor = 1 + CONSTANT \times \sqrt{Engine\ Hours}$$

AIR's results indicate that at 66 hours of use, the HC+NOx deterioration factor (DF) for a Phase 1 Class I OHV engine is 1.4, and for a Phase 1 Class II OHV engine at 250 hours of use, the HC+NOx DF is 1.4. Multiplying these DF's times the Phase 1 standards result in a conservative estimate of the in-use emission rate of Phase 1 OHV engines. The Class I OHV estimate at 66 hours is 1.4 * 16.1 g/kW-hr = 22.5 gr/kW-hr, and for Class II OHV engines at 250 hours, 1.4*13.4 g/kW-hr= 18.8 gr/kW-hr.

The Agency analyzed a subset of the data examined by AIR, namely, the field tested engine data. EPA performed an ordinary least square analysis of HC+NOx deterioration factor (DF) versus usage in hours for the square root of hours function shown above. The Agency's results predict that at 66 hours, the Class I OHV HC+NOx DF is 1.35, and for Class II OHV at 250 hours 1.73. The Agency's analysis produced very similar results to the AIR analysis for a Class I OHV, but higher results for a Class II OHV. The Agency believes the difference in the Class II OHV DF estimate is likely a result of the different methodologies used by AIR and by EPA, specifically, the Agency's analysis did not include new engine quality audit data, manufacturer sales information, or individual engine manufacturers engineering judgement. Due to the similarities in the HC+NOx DF estimate for the Class I OHV, and the Class I and II SV engines (see Section 3.2.4.3), the Agency is comfortable relying on the industry estimate for Class II OHV engines.

Based on discussions with several of the engine manufacturers who provided test data to AIR, the Agency believes that the majority of the field aged engines used in this study would be considered typical of residential application engines, i.e., engines which are designed for relatively low useful lives. However, at the Agency's request, manufacturers identified a small sample of Class II OHV engines which were considered to have design characteristics representative of a 500 hour useful life engine. a discussion of the EPA analysis of this data is contained in the public docket for this rule.(Ref. 17) This analysis indicated an HC+NOx DF on the order of 1.2 at 500 hours. The Agency's conclusion, based on this very small data set, is that Class II OHV engines designed for a 500 hour useful life had very similar, and perhaps better, HC+NOx deterioration at 500 hours compared to Class II OHV engines designed for a 250 hour useful life do at 250 hours. Unfortunately, the AIR data set did not contain field aged data on Class I OHV engines which have design characteristics representative of a 250 or 500 hours useful life engine, nor did it contain field aged data on Class II OHV engines with design characteristics representative of 1,000 hour useful life engine.

3.2.5.3.2. Improvements to Phase 1 Technology OHV Engines -- The Agency considered several improvements to Phase 1 OHV technology during the development of the Phase 2 proposal. Based on information contained in an 1996 report prepared by ICF Inc. (see ref. 1 of this Chapter, ICF, 1996), and a 1996 report prepared by Southwest Research Institute (see ref. 3 of this Chapter, SwRI, 1996), several improvements to Phase 1 OHV technology was considered, a summary of which is provided here. However, it should be noted that for Class I OHV engines improvements to existing production has little practical meaning for the majority of the market, because only approximately 10 percent of the Class I market is made up of OHV technology and most are expected to already be below the proposed Phase 2 standard. For the majority of the Class I market, the more relevant discussion is contained in Section 3.2.6, "Conversion of SV to OHV design for 4-stroke engines".

One area considered by the Agency was improvements to combustion chamber design and intake systems. Improvements to combustion chamber designs can result in more complete combustion of the air/fuel mixture, and may improve the engines ability to operate at leaner air/fuel mixtures (see ICF 1996, Chapter 5.1, and SwRI 1996, Chapter 6). Redesigning the intake system can result in additional charge swirl within the combustion chamber for a more homogenous charge which can result in more complete combustion.

The Agency also considered improvements to the piston and piston ring design, and cylinder bore smoothness. The objective of these improvements would be to improve oil control. Poor oil control can result in the formation of combustion chamber deposits, which will increase the in-use emissions from an engine (see ICF 1996, Chapter 5.1, and SwRI 1996, Chapter 6). Some Phase 1 OHV engines have likely already incorporated improvements to improve oil control, however, for those engine models which have not, the Agency believes improvements to the piston and piston ring design may be necessary to reduce oil consumption. In addition, improvements to cylinder roundness and finish may also be required to reduce oil consumption.

The ICF 1996 report contains a detailed discussion of the per engine costs of applying these improvements to Phase 1 technology Class I and II OHV engines (see ICF 1996, Chapter 5). As presented in the ICF 1996 report, per engine costs are effected by engine family production volumes. ICF analyzed costs for engine families based on production volumes of 35,000 units, 200,000 units and 1,200,000 units for nonhandheld engines. The Agency believes the 1.2 million estimate is not appropriate for nonhandheld Class I or II engines, because there are no OHV engine families being produced with annual production volumes near 1.2 million. Table 3-05 presents a summary of the per-engine costs associated with improvements to nonhandheld OHV technology.

TABLE 3-05
Estimated per Engine Costs for Improvements to Class I and Class II OHV Engines

Improvements to Phase 1 Class I and II OHV Engines	Per Engine Costs for Family w/ 35,000 Units Annual Production	Per Engine Costs for Family w/ 200,000 Units Annual Production
Combustion and Intake Systems	$3.05	$0.53
Piston and Ring Designs	$4.60	$2.67

The improvements the Agency has examined for OHV engines would primarily be expected to reduce in-use HC+NOx emission deterioration. Based on the information presented in Table 3-05, the Agency estimates that improvements to a Class I or Class II OHV engine could cost up to between $3.20 and $7.65 per engine, depending on the improvements required and the engine family annual production volume. The Agency estimates these improvements would reduce the in-use deterioration of Phase 1 OHV engines to an average HC+NOx DF level of 1.3 at the engines useful life.

Appendix B contains a list of engine families certified to the Federal Phase 1 regulation. The Agency also has access to manufacturer's confidential production volume projections for each engine family. As of September, 1997, approximately 8.0 million Class I engines and 2.5 million Class II engines had been certified, based on historical sales data this would appear to be the majority of nonhandheld engines sold in a single year. Using this confidential sales information, the sales weighted certification level is 10.6 g/kW-hr for

Class I OHV engines, and 8.3 g/kW-hr for Class II OHV engines. Based on the Agency's experience with on-highway heavy duty engines, the Agency estimates a typical compliance margin used by manufacturers to be between 10 and 20 percent. By achieving an HC+NOx DF of 1.3, combined with a compliance margin between 10 and 20 percent and the sales weighted Phase 1 certification levels, the Agency estimates improvements to Class I OHV engines would achieve an in-use emission rate between 15.2 and 16.5 g/kW-hr at 66 hours, and Class II OHV engines would achieve an in-use emission rate between 11.9 and 12.9 g/kW-hr at 250 hours, the ranging representing a range in estimated manufacturer compliance margin between 10 and 20%. However, it should be noted that only about 10 percent of Class I engines currently certified to the Phase 1 regulation are OHV technology. The performance of these specific Class I engines may not be representative of what would occur if all Class I engines were converted to OHV technology.

3.2.5.4 Impact on Equipment Design and Use -- As discussed previously, OHV technology has been used for many years in nonhandheld equipment. The improvements to OHV technology described in this section would have no negative impacts on nonhandheld equipment design and use, since most of the improvements discussed are internal to the engine and would not effect the overall shape or functionality of the engine with respect to it's use in a piece of equipment.

3.2.5.5 Technology Impact on Noise, Safety, and Energy -- The Agency expects no negative impacts on the noise level or the operational safety from improvements to Phase 1 technology OHV engines. As discussed in Section 3.2.5.3, the Agency considered internal improvements to OHV engines, which would have no impact on noise levels or safety.

The Agency expects no significant changes in the energy consumption from improvements to Phase 1 technology OHV engines. The improvements considered by the Agency (<u>see</u> Section 3.2.5.3) would reduce the in-use HC and NOx deterioration of the engines, but would have only marginal, if any, effects on fuel consumption.

3.2.6 Conversion of SV to OHV Design for 4-Stroke Engines

This section contains information regarding the costs and benefits of converting Phase 1 technology SV engines to OHV technology engines. In this analysis of costs and benefits, the Agency considered the conversion not simply to OHV technology, but to emissions optimized OHV engines, which would incorporate designs for improved new engine and in-use emission performance beyond existing Phase 1 technology OHV engines. The converted SV engines were assumed to have the improvements discussed in Section 3.2.5 incorporated. Therefore the new OHV engines would have similar new and in-use emission performance as the improved Phase 1 OHV engines described in Section 3.2.5.3. Rather than repeat the information contained in Section 3.2.5, this section will refer to that section, and the information presented here will mainly describe the required changes and costs to convert Phase 1 technology SV engines to OHV designs.

3.2.6.1 Description of Technology for SV to OHV Conversion -- The technology discussed in this section is OHV technology, a brief description of which is contained in Sections 3.2.4.1 and 3.2.5.1, and additional information on OHV technology is contained in Chapter 2 of ICF, 1996 (<u>see</u> ref. 1 of this Chapter).

3.2.6.2 Current State of Technology Development for SV to

OHV Conversion -- As discussed in Section 3.2.5.2, OHV designs and manufacturing information is well known by small engine manufacturers, therefore, the Agency believes design and manufacturing techniques for OHV engines is also well known to small engine manufacturers.

3.2.6.3 Exhaust Emission Performance and Costs of SV to OHV Conversion -- The information contained in Section 3.2.5.3 on the emission performance of improved OHV engines are the same estimates the Agency believes are appropriate for the new OHV engines which have been converted from SV designs. As stated in Section 3.2.5.3, the Agency estimates a Class I OHV engine can achieve an in-use emission rate between 15.2 and 16.5 g/kW-hr at 66 hours, and Class II OHV engines can achieve an in-use emission rate between 11.9 and 12.9 g/kW-hr at 250 hours.

The Agency relied on the cost estimates contained in Chapter 3 of ICF, 1996 (see ref. 1 to this Chapter). In the ICF report, estimates were provided on the cost of converting existing SV production capabilities to OHV manufacturing. This report contains estimates of costs for variable manufacturing costs and fix costs. Variable manufacturing costs include includes material costs, components costs, and manufacturing labor. Fixed cost estimates include engineering costs, changes to technical support training and manuals, and changes in tooling costs. Table 3-06 contains a summary of the estimates used by the Agency from the ICF, 1996 report.

TABLE 3-06
Summary of per Engine Cost for Conversion from SV to OHV Technology by Class and Engine Family Annual Production (data from ICF, 1996)

Conversion of Phase 1 SV Engines to OHV Technology	Class II, 35,000 units	Class II, 200,000 units	Class I, 35,000 units	Class I, 200,000 units	Class I, 1,200,000 units
Variable Costs	$8.59	$8.59	$4.94	$4.94	$4.94
Fixed Costs	$8.66	$1.62	$8.66	$1.62	$0.44
Totals	**$17.25**	**$10.21**	**$13.60**	**$6.56**	**$5.38**

The costs estimates listed in Table 3-06 are lower than the values reported by ICF. As discussed in Chapter 4.2.1 *Market Mix and Cost Estimates - Nonhandheld Engines* of this draft RSD, the Agency believes ICF over-estimated the time needed to manufacturer several OHV components. As discussed in Chapter 4.2.1, the Ageny's revised estimate lowered the variable costs by $4.29 per engine. Based on this information, the Agency estimates the cost of converting Class I SV to OHV engines costs between $5.38 and $13.60 per engine and the cost of converting Class II SV to OHV technology costs between $10.21 and $17.25 per engine, depending on the annual production of the engine family.

3.2.6.4 Impact on Equipment Design and Use of SV to OHV Conversion -- SV and OHV engines are similar in many ways from an overall packaging perspective. The Agency expects that for many applications new OHV designs will present no changes for equipment manufacturers from a design perspective. However, for some equipment types, the change in cylinder head configuration for the OHV or increases in cylinder head and/or exhaust gas temperature will require changes in equipment design. Chapter

4.4.1. of this draft RSD, “Nonhandheld Equipment”, contains a detailed description of the equipment design changes the Agency would expect to see from conversion to OHV.

The Agency expects no changes in the use of equipment from the conversion to OHV technology, from the perspective of the user, SV and OHV engines should perform the same way with respect to power generation.

3.2.6.5 Technology Impact on Noise, Safety, and Energy for SV to OHV Conversion -- The Agency expects no significant changes in the noise or operational safety of engines from the conversion of SV engines to OHV technology. OHV engines are widely used in the nonhandheld market, and there are no technical reasons the Agency is aware of which would cause an increase in noise, or present an unsafe technology, from of the conversion to OHV engines.

The Agency would expect improvements in fuel economy from the conversion of SV engines to OHV technology. Chapter 4.6.1 of this draft RSD, “Fuel Consumption”, contains additional information on the expected fuel savings from the conversion to OHV technology. OHV engines are more fuel efficient than SV designs, and the Agency expects to see approximately a 15 percent reduction in the fuel consumption from OHV engines compared to SV engines.

3.2.7 Application of Catalytic Convertors to 4-stroke nonhandheld Engines

The information presented in Section 3.2.2 on catalysts and handheld engine in general is also relevant for the discussion of the application of catalysts to nonhandheld engines, particularly the discussion of new and in-use exhaust emission performance.

Federal certification information for the Phase 1 regulation indicates that a small number of Class 1 and Class 2 engine families have been certified using catalyst technology on 4-stroke SV and OHV engines. These catalyst equipped 4-stroke engines have all been designed for use in indoor applications, primarily for propane fueled floor buffers. The projected sales for these engines represent less than 1 percent of nonhandheld engine sales.

Based on the similar needs for catalysts, assembly, muffler/heat shield needs and fixed costs, the Agency estimates similar costs would be added to 4-stroke engines as is predicted for 2-stroke nonhandheld engines in Section 3.2.2 for the addition of catalysts, e.g., in the range of $6 to $12 per engine. However, it is likely a catalyst for a nonhandheld engine would need to be larger and would therefore be expected to be more expensive. a detailed analysis of the costs associated with applying a catalyst to nonhandheld engines was not performed, so these numbers should only be considered rough estimates, and not as reliable as the estimate for 2-stroke engine.

As with the discussion of handheld engines, the Agency has little information on the performance of catalysts on in-use, field aged engines. This lack of information makes an accurate estimate of in-use performance difficult.

3.2.8 Discussion of Other Engine Technologies

The Agency is aware there are additional technologies not discussed in this draft RSD. These include electronic fuel injection, three-way catalyst with closed loop air/fuel control, direct-injection two-stroke technology, and stratified charge. In addition, Chapter VII of the SwRI 1996 report (<u>see</u> ref. 3

to this Chapter) contains a summary of over 40 papers published by the Society of Automotive Engineers which relate to various technologies which may be applicable to handheld engines.

The Agency has not afforded these technologies the same in-depth analysis given presented in Sections 3.2.1 thru 3.2.7 for a variety of reasons. These include factors such as unknown emission performance, no in-use performance data, unknown application to small engine equipment, and unknown or high costs. The Agency request additional information on technologies which may be applicable to small engines. Information on the type of technology, a complete description of the technology, new and in-use engine emission performance, and manufacturing costs would be appropriate.

3.3 Proposed Exhaust Emission Standards

This section contains information the Agency used to determine the appropriate standards contained in the proposal. Additional information is contained in the Preamble for this Notice of Proposed Rulemaking.

3.3.1 Proposed HC+NOx Standards for Class I Engines

The Agency is proposing a corporate average exhaust emission level of 25g/kW-hr HC+NOx for Class I engines beginning in model year 2001. This proposed standard is applicable for all three useful life categories of 66, 250, and 500 hours. The Agency believes this level is technologically feasible, and as discussed previously can be met by improvements to existing Class I SV engines. The Agency has performed an analysis using the existing Phase 1 certification data (which contains confidential sales projections) combined with reasonable assumptions for in-use deterioration. This analysis indicates a standard of 25 g/kW-hr is achievable with improvements to existing SV engines and considering the emission performance of existing Phase 1 OHV engines. A standard of 25g/kW-hr would not require an increase in the penetration of Class I OHV sales. Manufacturers will need to make improvements to existing SV engine families which will require improvements to several engine components, however, major retooling of engine production lines will not be required. In addition, the use of ABT provides manufacturers with considerable flexibility for determining the most appropriate expenditure of resources when deciding which engine families will need specific improvements to meet the proposed levels. The time between the finalization of this rule and model year 2001 will be sufficient for manufacturers to meet the proposed HC+NOx level.

The Agency believes a level more stringent than the proposed 25g/kW-hr HC+NOx is not appropriate for a Federal standard at this time. As discussed above, a level more stringent than 25 g/kW-hr could be met by the conversion of existing SV technology engines to OHV technology. As discussed previously (<u>see</u> Section 3.2.5.2), the percentage of Class I OHV engine sales has remained fairly constant for the past eight years, despite superior durability, performance, and fuel economy. Several Class I engine manufacturers, including the two largest which represent the majority of the market in terms of sales, have discussed with the Agency their attempts to sell low cost OHV engines in the past. Manufacturers have indicated they have seen little success in drawing consumers away from the even lower cost Class I SV engines. Engine manufacturers have indicated that the principle reason for the failure of OHV's to penetrate further into the Class I market is the cost difference between the two engine technologies, and consumers unwillingness to pay this premium. Several engine manufacturers have indicated that low cost Class I SV engines have manufacturing costs on the order of $60 to $70 per engine. Engine manufacturers contend that for these low cost engines, the cost increase to purchase a OHV engine is large enough to prevent a larger market penetration by OHV engines market (see 62 FR 14752, "Class I OHV Demonstration Program"). The Agency estimates the cost difference between improvements to Phase 1 SV versus the conversion of Phase 1 SV to OHV to be between $1.42 and $7.02 per engine (see Sections 3.2.4.3 and 3.2.6.3). Engine manufacturers have indicated concern over what they perceive to be the potentially dramatic impacts on the Class I engine sales which would result from a standard which requires conversion to OHV technology. The Agency requests comment on the market concerns expressed by engine manufacturers.

The Agency has considered the cost associated with the conversion of Class I SV to OHV technology and compared it to the costs associated with improvements to existing SV engines. Considering the manufacturers concerns regarding the potential negative market impacts of more costly standards the Agency believes the proposed 25 g/kW-hr HC+NOx level is the appropriate level for Class I engines at this time.

3.3.2 Proposed HC+NOx Standards for Class II Engines

The Agency is proposing a corporate average HC+NOx emission standard of 12.1 g/kW-hr which will be phased in over five years, beginning in model year 2001. The HC+NOx phase-in standards would be 18.0g/kW-hr in model year 2001, 16.6 in 2002, 15.0 in 2003, and 13.6 in 2004. These proposed standards are applicable for all three proposed useful life categories of 250, 500, and 1000 hours. Based on the information presented in this Chapter, the Agency believes an in-use level of 12.1g/kW-hr can be met by the conversion of Phase 1 SV engines to OHV technology (see Section 3.2.6), and by internal improvements to some existing Phase 1 OHV engines (see Section 3.2.5).

The proposed standards would require significant production line changes for many Class II engine manufacturers to convert existing SV models to OHV designs, as well as modifications to some Phase 1 OHV models which may need internal improvements to meet the 12.1 g/kW-hr level. To accommodate a smooth transition of existing SV engine family production lines to the new OHV technology or other comparably clean technology, the Agency is proposing a five year phase-in period, starting with a level of 18 g/kW-hr in 2001 and ramping down to the final year level of 12.1 in model year 2005. The Agency expects the proposed standards for Class II engines would result in increased penetration of and conversion to clean OHV technology by 2005. However, the proposal does not preclude other technologies from meeting the proposed standard.

The Agency recognizes that there are large differences in technology mixes currently being produced by Class II engine manufacturers. Some Class II engine manufacturers have already made significant investments in OHV technology prior to and during the Phase 1 program, for some of these manufacturers the standards in the early years of the Phase 2 phase-in (i.e., the 2001 standard of 18g/kW-hr and the 2002 standard is 16.6 g/kW-hr) may not require additional reductions in Class II engine emissions. At the same time, the Phase 1 standards do not require a shift to clean, durable OHV technology or comparably clean technology, and several Class II engine manufacturers currently produce a significant number of SV engines. For manufacturers who are relying on SV technology the proposed phase-in period will allow them to shift their production to new, cleaner technology which is capable of meeting the 2005 standard of 12.1g/kW-hr. The Agency believes the phase-in standards will address the inequities among manufacturers current technology mixes but will also require manufacturers to produce the clean, durable 12.1g/kW-hr engines in 2005. Manufacturers have indicated the early banking provision will pull ahead clean technology and ease the transition to the 12.1 standard. However, due to the wide discrepancy between manufacturers current technology mix, some manufacturers may generate significant credits during the phase-in period. The Agency has performed an analysis, based on Federal Phase 1 certification data, which indicates under some conditions early banking would result in significant credits being generated during the phase-in period which may in fact undermine the 12.1g/kW-hr standard in model year 2005. To this this does not occur, the Agency has proposed certain restrictions in the ABT program, as discussed in the Preamble for this proposal, Section IV.A.5.

A level more stringent than 12.1 g/kW-hr HC+NOx would require technology other than an emissions-optimized OHV engine, such as the addition of catalyst technology. As noted earlier, the Agency has insufficient information regarding the costs and in-use performance of catalyst technology to propose a standard based on catalysts for Class II engines.

3.3.3 Proposed HC+NOx Standards for Class III, IV and V Engines

The Agency is proposing an in-use HC+NOx standard of 210, 172 and 116 g/kW-hr for Class III, IV, and V engines, respectively. These standards would be applicable for both of the proposed useful life categories of 50 and 300 hours.

The proposed standards begin in model year 2002, with a requirement that 20 percent of a manufacturer's U.S. sales meets the standards, followed by 40 percent in 2003, 70 percent in 2004, and 100 percent in model year 2005.

The Agency expects the proposed in-use standards can be met through improvements to existing Phase 1 technology 2-stroke engines. As discussed in Section 3.2.1 the Agency believes improvements to Phase 1 technology 2-stroke engines will result in approximately a 30 percent reduction in the in-use emissions of Phase 1 engines, which would be required to meet the proposed standards.

PPEMA members have indicated the proposed standards would require significant research and development time as well as a large capital investment to change existing production capabilities. The phase-in period plus the lead time anticipated after this rule is finalized will allow manufacturers at least 6 years to make the necessary changes to existing product lines in order to meet the proposed standards which should accommodate the manufacturers concerns regarding lead time.

The Agency has not proposed a standard which would require catalyst or 4-stroke technology. The Agency has little information regarding the in-use performance of a 2-stroke engine equipped with a catalyst. The Agency's experience with on-highway technology indicates catalysts and engine technology evolved together to prevent significant in-use deterioration. Therefore, data on the in-use performance of catalyst technology must be collected and analyzed to determine if catalysts are feasible for handheld engines. Two engine manufacturers have introduced 4-stroke engines into string trimmer applications. There are likely some applications, such as high power chainsaws, where 4-stroke technology may not be feasible as a power unit because of weight concerns. As previously discussed (see Table 3-03 in Section 3.2.3.3), the Agency estimates that conversion to 4-stroke designs would cost between $7.26 and $9.62 per engine. PPEMA has reported that in 1993 and 1994 the average retail price of a 2-stroke gasoline powered string trimmer or leaf blower was approximately $100, and the average retail price of a chainsaw was approximately $200.(Ref. 18) PPEMA members have expressed concern regarding what they perceive to be the potential negative impacts on sales which would result from a large increase in engine costs, such as the cost of conversion to 4-stroke technology for handheld engines. The Agency requests comment on the market concerns expressed by engine manufacturers.

The Agency believes that during the next several years additional information regarding the in-use performance of new technologies, such as handheld 4-strokes, or traditional 2-strokes equipped with catalyst, may become available, perhaps in response to the CARB Tier 2 program. In addition, EPA recognizes that technological advances and/or cost reductions may occur after promulgation of the Phase 2 rule that could make greater, but still cost-effective reductions feasible in handheld emission levels. The Agency proposes to conduct a technology review to address this possibility. In this review, EPA expects to examine issues including the potential for further reductions from existing 2-stroke engines, stratified charge 2-stroke technology, direct injection 2-stroke injection, the use of catalysts on handheld engines, and the conversion to 4-stroke technology. Following a technical review, the Agency proposes to publish a Notice of Proposed Rulemaking in 2001 announcing any intended amendments to the standard levels or other program elements, or EPA's intention to maintain the existing handheld standards or program. The Agency proposes that the final rulemaking would be completed by 2002 and, if adopted, Phase 3 standards would be phased in on a percentage basis and over of a period of time similar to Phase 2, beginning no earlier than model year 2007. This schedule is intended to provide a minimum five year period before the implementation of any Phase 3 standards to allow manufacturers to recoup their investments in Phase 2 technology.

Chapter 3 References

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