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Spark-Ignition Engine Emission Deterioration Factors for the Draft NONROAD2004 Emissions Model

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Assessment and Standards Division
Office of Transportation and Air Quality
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For the draft NONROAD2004 Emissions Model

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I. <u>Purpose</u>

This report addresses the emission deterioration rates for spark-ignition engines currently being used in the draft NONROAD2004 model. The specific deterioration inputs used in NONROAD and their basis will be addressed for spark-ignition engines at or below 25 horsepower and over 25 horsepower, as well as liquid petroleum gas (LPG) and compressed natural gas engines (CNG). Deterioration inputs for compression-ignition (diesel) engines are addressed in the report, Exhaust Emission Factors for Nonroad Engine Modeling - Compression Ignition (NR-009b). The EPA welcomes comments and suggestions concerning our approach to modeling nonroad engine emissions deterioration.

The previous version of this report contains discussions of the deterioration inputs used in the original 1998 draft of the NONROAD model and sources of deterioration rates which have been considered by EPA. It has been included as an appendix in this report for ease of reference.

II. <u>Background</u>

As used here, the term "deterioration" refers to the degradation of an engine's exhaust emissions performance over its lifetime due to normal use or misuse (i.e., tampering or neglect). Engine deterioration increases exhaust emissions, usually leads to a loss of combustion efficiency, and can in some cases increase nonexhaust emissions. The amount of emissions increase depends on an engine's design, production quality, and technology type (e.g., spark ignition two-stroke and four-stroke, compression ignition). Other factors, such as the various equipment applications in which an engine is used, usage patterns, and how it is stored and maintained, may also affect deterioration.

The term "deterioration rate" refers to the degree to which an engine's emissions increase per unit of activity. Nonroad engine activity is expressed in terms of hours of use or fraction of median life. The term "deterioration factor" refers to the ratio of an engine's emissions at its median life divided by its emissions when new.

The terms *useful life* and *median life* are used in the following manner in this report in order to avoid confusion. *Useful life* is a regulatory term used to indicate the amount of time during the life of a nonroad engine that a manufacturer must certify to the U.S. EPA that the engine meets a required emission standard as defined by a regulation. *Median life,* as used in this report, refers to the age at which 50 percent of the engines sold in a given year have ceased to function and have been scrapped.[1]

III. Core Challenge

The core challenge associated with estimating nonroad engine deterioration is the development of reasonably accurate deterioration rates for the enormous range of nonroad engine types and applications from the limited amount of nonroad emission deterioration data that exist at this time. To estimate deterioration, the emission performance of engines at various ages is required. Such information can be obtained from a longitudinal study that examines the same set of engines periodically as they age, or from a sampling study that tests engines of various ages but the same basic design. In either case, the engines studied should be selected randomly from the population of engines actually being used in the field.

Given the limited available test data, EPA is currently unable to develop unique deterioration rates based on actual engine test data for the myriad of applications and power levels covered by NONROAD. The Office of Transportation and Air Quality has conducted emissions testing on several dozen small spark ignition lawn & garden engines and a few large compression-ignition engines. The nonroad engine industry and a few States have also conducted some nonroad engine emissions testing. However, the nonroad engine emissions data currently available are still limited when compared to the large number of nonroad engine types and applications for which these engines are used, particularly for the purposes of evaluating emission deterioration as engines age. The EPA has obtained extensive data on the emissions deterioration of light-duty highway engines, but these engines are unlikely to deteriorate in a fashion typical of nonroad engines due to fundamental differences in engine and emission control technology design, maintenance, and operation. Deterioration in emissions from light-duty vehicles (LDVs) is thought to be due in large part to gross failures of emission control after-treatment systems, which nonroad engines do not have at this time.

A related challenge is that the EPA has essentially no data on the incidence of tampering and/or neglect of proper maintenance and only limited data that distinguish the effect of such malmaintenance from the effects of normal usage. These data are based on emission tests of two lawnmower engines that had various components, including the sparkplug, air filter, and oil, manipulated to simulate bad maintenance practices (i.e., not changing the sparkplug, air filter and oil on a regular basis, as recommended by the manufacturer). The results of this effort were inconclusive, suggesting that intentional disablement of engine components does not adequately simulate emissions deterioration from normal usage. The EPA requests that state and industry stakeholders share any data regarding the incidence of tampering and neglect of proper maintenance they may have. The EPA also requests that stakeholders share any data they have regarding the relationship between emissions deterioration due to normal usage and emissions deterioration due to intentional disablement of engine components.

IV. Method of Applying Deterioration In NONROAD

Generally, the NONROAD model addresses the effects of deterioration in the inventory calculation by multiplying a zero hour emission factor for each category of engine by a deterioration rate as the engine ages. The following formula describes the basic form of the calculation:

$$EF_{aged} = EF_o * DF \tag{1}$$

where: EF (aged) is the emission factor for an aged engine
EF_o is the emission factor for a new engine
DF is the deterioration factor.

In order for the NONROAD model to be compatible with the EPA's small nonroad spark ignition engine rulemaking process and also be able to calculate deterioration for other engines, we have derived the following multi-purpose deterioration function:

$$\begin{aligned} DF &= 1 + A * (\text{Age Factor})^b \quad && \text{for Age Factor} \le 1 \\ DF &= 1 + A && \text{for Age Factor} > 1 \end{aligned} \tag{2}$$

where $\text{Age Factor} = \dfrac{[\text{Cumulative Hours * Load Factor}]}{\text{Median Life at Full Load, in Hours}}$

A, b = constants for a given technology type; $b \le 1$.

The constants A and b can be varied to approximate a wide range of deterioration patterns. "A" can be varied to reflect differences in maximum deterioration. For example, setting A equal to 2.0 would result in emissions at the engine's median life being three times the emissions when new. The shape of the deterioration function is determined by the second constant, "b." This constant can be set at any level between zero and 1.0; currently, the NONROAD model sets "b" equal to either 0.5 or 1.0. The first case results in a curvilinear deterioration rate in which most of the deterioration occurs in the early part of an engine's life. The second case results in a linear deterioration pattern in which the rate of deterioration is constant throughout the median life of an engine. In both cases, the EPA decided to cap deterioration at the end of an engine's median life, under the assumption that an engine can only deteriorate to a certain point beyond which it becomes inoperable. For spark ignition engines at or below 25 horsepower, NONROAD uses the regulatory useful life values in Appendix F of the Phase 1 regulatory support document for median life values. For other engines, NONROAD uses the median life values from the Power Systems Research (PSR) database.[2] These functions can be used to provide a close approximation to the shape of the deterioration curves used in

NSEEM1 and NSEEM2 (regulatory models for the Phase 1 and 2 Small Spark-Ignition Rules) for spark ignition engines less than 25 horsepower.

SI engines have a wide range of designs that affect their emissions deterioration. To model these different deterioration patterns, NONROAD categorizes SI engines into "technology types" by their design and emission control equipment. A given technology type can apply to one or more horsepower-application categories, and a given horsepower-application category can be divided into more than one technology type. NONROAD applies a given deterioration function (that is, a given A and b value) to all engines of a given technology type, regardless of their application or power range. As a result, a single technology type may be applied to engines with very different median lives, but this difference is handled by expressing engine age in terms of the "Age Factor" defined above. The EPA believes this approach is reasonable, since deterioration patterns should be more closely related to the design of the engine and its emission control technology than to the kind of application in which it is used. Furthermore, the available data on emissions deterioration of nonroad SI engines is insufficient to develop separate deterioration functions for the many combinations of application, horsepower range, and technology type.

NONROAD's technology type feature allows each horsepower-application category to be divided into as many as ten technology types, each with its own deterioration pattern. The technology type feature gives the model flexibility to handle the full range of engine designs used in nonroad equipment. For example, the technology type feature can handle the 33 distinct engine types that are defined by EPA's Phase 1 and 2 Small Engine Rules, as shown in Tables 1 through 5. However, deterioration data for each technology type across different applications are not available at the present time. Thus, the NONROAD model does not apply different deterioration patterns to engines of the same technology type used in different applications. Instead, the model applies different deterioration patterns to engines within each engine type (i.e., two-stroke and four-stroke spark ignition) based on the more detailed engine classes defined in the Phase 1 and 2 Small Engine Rules, the proposed Large Spark-Ignition Equipment, Recreational Marine and Recreational Equipment Rule, instead of by application. In other words, NONROAD models deterioration for a tiller and a lawn mower equipped with engines of the same technology type using the same deterioration pattern.

V. Deterioration Inputs For Engines At or Below 25 Horsepower

A. Deterioration Inputs Used In NONROAD For Spark Ignition Engines Less than 25 Horsepower

In the draft NONROAD2004 model, the constant ‘b’ is set at 0.5 for four-stroke engines, resulting in a square root relationship between age and deterioration. The constant ‘b’ is set at 1.0 for two-stroke engines, which produces a linear relationship between age and deterioration. This use of a curvilinear deterioration pattern for four-stroke engines and a linear deterioration pattern for two-stroke engines is similar to the approach used in the NSEEM2 model used for the Phase 2 Small Engine Rule.

The inputs for the variable ‘A’ of the NONROAD deterioration function are shown in Tables 1-5 for the small engine classes defined in the Phase 1 and 2 Small Engine Rules. EPA derived the deterioration values for Phase 2 engines with catalysts (G2HxC2) and set NOx deterioration values to zero based on analyses done during the development of the Phase 2 rule.[3] For the other types of small engines included in the Phase 1 and 2 rulemakings, the values came from the Phase I Regulatory Support Document for maximum life emission factors and new engine emission factors. It should be noted the HC deterioration ‘A’ value (0.201) for snowblowers (G2GT25) is the same as that used for baseline Class 1 and 2 two-stroke nonhandheld engines (G1N1 and G2N2).

For each pollutant and each engine type, variable ‘A’ represents the maximum deterioration rate reached at one median life. It should be noted that particulate matter (PM) standards were not considered or included in the Phase 1 and Phase 2 Small Engine Rules, and little data exists for PM deterioration rates. Based on EPA’s best judgement at this time, PM deterioration in two and four-stroke engines are equated to that of HC in the draft NONROAD2004 model. The EPA requests stakeholders with information about the PM emissions deterioration of two-stroke engines to submit such data.

The deterioration rates used in NONROAD for small engines covered under the Phase 1 and 2 Small Engine Rules approximate the levels of deterioration found in testing, including the testing summarized in NEVES and the testing done to support the Phase 1 and 2 Small Engine Rules. Where these test results differ, the EPA has chosen to give greater weight to data taken from engines which have experienced usage patterns that reflect expected field conditions. The test data submitted to EPA for the Phase 2 Small Engine Rule, for example, reflects testing of engines that have undergone accelerated aging which EPA does not believe to be representative of the aging experienced by engines in use. After evaluating all available data, the EPA has determined that the level of deterioration used in NSEEM1 and Phase 1 Small Engine Rule provides a reasonable basis for the deterioration rates used in NONROAD. These deterioration rates are generally higher than the deterioration rates used for regulatory purposes in NSEEM2 and the Phase 2 Small Engine Rule, but are generally smaller than those used in NEVES. The EPA believes that the deterioration rates used in NONROAD are more reflective of the deterioration rates that one would expect to find out in the field when equipment powered by small spark ignition engines is used by the average person than are the deterioration rates found in NSEEM2 and the Phase 2 Small Engine Rule.

It should be noted that EPA increased HC deterioration rates for two-stroke engines with catalysts that small engine manufacturers plan to use in handheld equipment (Classes 3, 4, and 5) based on additional analyses for the final Phase 2 Rule. However, the EPA did not update the PM deterioration rates for these engines to match the revised HC deterioration rates. This was an oversight and will be in the next update of the model. EPA welcomes any comments or information concerning PM deterioration rates for these types of engines.

There are some small engine applications that are not covered by the Phase 1 or 2 Small Engine Rules. These include marine engines (SCC 2282xxxxxx) and certain recreational equipment such as snowmobiles (226x001020), off-road motorcycles, all-terrain vehicles (226x001030), and specialty vehicle carts (226x001060). In NONROAD the two-stroke versions of the recreational equipment engines are assigned deterioration values equal to the G2N2 tech type shown in Table 2, but they use a tech type name of R12S since the emission factors differ from the other engine applications. Four-stroke versions of these recreational equipment engines use deterioration rates based on pre-1978 uncontrolled four-stroke on-highway motorcycles from the MOBILE model.[4]

Recreational marine engines are handled differently from the recreational equipment engines. Based on information gathered for the recreational marine engine rulemaking (61 FR 52087, October 4, 1996), two-stroke marine engines are modeled as having no deterioration. We request comment on whether this should be changed to model two-stroke marine engine deterioration similarly to other two-stroke engines or possibly use some other deterioration rate.

Table 1
Class 1 (Displacement < 225 cc) Nonhandheld Deterioration Factor A

Engine Tech Type	HC	CO	NOx	PM	BSFC
G2N1 (gas 2-stroke nonhandheld Class 1, baseline)	0.201	0.199	0	0.201	0
G4N1S (gas, side-valve, 4-stroke nonhandheld Class 1, baseline)	1.1	0.9	0	1.1	0
G4N1O (gas, overhead valve, 4-stroke nonhandheld Class 1, baseline)	1.1	0.9	0	1.1	0
G2N11 (2-stroke, Phase 1)	0.266	0.231	0	0.266	0
G4N1S1 (Phase 1 side-valve, 4-stroke)	5.103	1.109	0	5.103	0
G4N1O1 (Phase 1 overhead valve, 4-stroke)	1.753	1.051	0	1.753	0
G4N1SC1 (Phase 1 side-valve, 4-stroke with catalyst)	5.103	1.109	0	5.103	0
G4N1S2 (Phase 2 side-valve, 4-stroke)	5.103	1.109	0	5.103	0
G4N1O2 (Phase 2 overhead valve, 4-stroke)	1.753	1.051	0	1.753	0

Table 2
Class 2 (Displacement ≥225 cc; Power Rating < 25 hp) Nonhandheld Deterioration Factor A

Engine Tech Type	HC	CO	NOx	PM	BSFC
G2N2 (gas 2-stroke nonhandheld Class 2, baseline)	0.201	0.199	0	0.201	0
G4N2S (gas, side-valve, 4-stroke nonhandheld Class 2, baseline)	1.1	0.9	0	1.1	0
G4N2O (gas, overhead valve, 4-stroke nonhandheld Class 2, baseline)	1.1	0.9	0	1.1	0
G4N2S1 (Phase 1 side-valve, 4-stroke with catalyst)	1.935	0.887	0	1.935	0
G4N2O1 (Phase 1 overhead valve 4-stroke)	1.095	1.307	0	1.095	0
G4N2S2 (Phase 2 side-valve)	1.935	0.887	0	1.935	0
G4N2O2 (Phase 2 overhead valve)	1.095	1.307	0	1.095	0

Table 3
Class 3 (Displacement < 20cc) Handheld Deterioration Factor A

Engine Tech Type	HC	CO	NOx	PM	BSFC
G2H3 (gas 2-stroke handheld Class 3, baseline)	0.2	0.2	0	0.2	0
G2H31 (Phase 1)	0.24	0.24	0	0.24	0
G2H3C1 (Phase 1 with catalyst)	0.24	0.24	0	0.24	0
G2H32 (Phase 2)	0.24	0.24	0	0.24	0
G2H3C2 (Phase 2 with catalysts)	0.72	0.24	0	0.24	0

Table 4
Class 4 (20cc ≤ Displacement < 50 cc) Handheld Deterioration Factor A

Engine Tech Type	HC	CO	NOx	PM	BSFC
G2H4 (gas 2-stroke handheld Class 4, baseline)	0.2	0.2	0	0.2	0
G2H41 (Phase 1)	0.29	0.24	0	0.29	0
G2H4C1 (Phase 1 with catalyst)	0.29	0.24	0	0.29	0
G4H41 (Phase 1 4-stroke)	1.1	0.9	0	1.1	0
G2H42 (Phase 2)	0.29	0.24	0	0.29	0
G2H4C2 (Phase 2 with catalyst)	0.77	0.24	0	0.29	0
G4H42 (Phase 2 4-stroke)	1.1	0.9	0	1.1	0

Table 5
Class 5 (Displacement ≥ 50cc; Power Rating <25 HP) Handheld Deterioration Factor A

Engine Tech Type	HC	CO	NOx	PM	BSFC
G2H5 (gas 2-stroke handheld Class 5, baseline)	0.2	0.2	0	0.2	0
G2H51 (Phase 1)	0.266	0.231	0	0.266	0
G2H5C1 (Phase 1 with catalyst)	0.266	0.231	0	0.266	0
G2H52 (Phase 2)	0.266	0.231	0	0.266	0
G2H5C2 (Phase 2 with catalyst)	0.626	0.231	0	0.266	0

VI. Deterioration Inputs for Spark Ignition Engines Greater than 25 Horsepower (19 kilowatts)

The deterioration factors currently used in NONROAD for recreational equipment (i.e., snowmobiles, all-terrain vehicles, and offroad motorcycles) and other large spark-ignition engines over 25 horsepower found in industrial and commercial equipment (e.g., forklifts, generators, compressors) are based on those used in the final rulemaking for recreational equipment and large spark-ignition engines.[5] Both these and the deterioration factors used for four-stroke recreational marine spark-ignition engines over 25 horsepower are based on on-highway deterioration data. For two-stroke recreational marine engines, no deterioration is assumed at this time based on data from the National Marine Manufacturers Association.[6]

At this time, EPA does not have deterioration data on large spark-ignition engines. However, EPA currently believes that larger uncontrolled carbureted gasoline nonroad engines would likely deteriorate more similarly to on-highway light-duty gasoline truck engines from the 1960's and 1970's.[7] These older on-highway engine models used similar technology as today's carbureted SD/I marine engines and large nonroad gasoline engines.

MOBILE5 includes emission factors and deterioration and tampering rates for on-highway heavy-duty gasoline engines. From this information, we can calculate the "A" value in Equation 2 by dividing the deteriorated emission factor at 100,000 miles by the new engine emission factor (and subtracting 1). To capture carbureted engines, we looked at the 20-year average for the 1960 through 1979 model years. Also, MOBILE5 uses linear deterioration for heavy-duty gasoline engines which translates to a "b" value of 1.0 in Equation 2.

As a check on these deterioration rates, we reviewed emission data from ten 1969 light-duty gasoline trucks in an EPA report titled "Procurement and Emissions Testing of 1969 and 1972/1973 Model Year Gasoline Powered Light Duty Trucks" (EPA-460/3-80-11). These trucks were emission tested in 1980 before and after engine maintenance. The ratio of the emissions before and after maintenance gives some insight into the emission deterioration of the engines. These data showed equivalent A values of 0.11 to 0.58 for HC, 0.31 to 0.39 for CO, and 0.05 to 0.10 for NOx. These data are consistent with the deterioration rates used in the draft NONROAD2004 model (see Appendix 1). The ranges of A values from the test data are due to reporting the averages with and without one truck that appeared to be an outlier.

At this time, we do not have any information on the deterioration of fuel-injected gasoline engines (without catalysts). MOBILE does not include emission rates for non-catalyzed engines with fuel injection because catalysts were introduced before fuel-injection into the on-highway market. Anecdotal information suggests that deterioration is low from these engines compared to deterioration in a catalyst. For instance, accepted emission deterioration test methods for current on-highway engines are performed by aging the catalyst to full life but using a relatively new engine. Because we do not have better information, EPA used the same deterioration coefficients for fuel-injected engines (without catalysts) as for carbureted engines.

To estimate the Phase 1 deterioration factors, we relied upon deterioration information for current Class IIb heavy-duty gasoline engines developed for the MOBILE6 emission model. Class IIb engines are the smallest heavy-duty engines and are comparable in size to many Large SI engines. They also employ catalyst/fuel system technology similar to the technologies we expect to be used on Large SI engines.[8]

To estimate the Phase 2 deterioration factors, we relied upon the same information noted above for Phase 1 engines. The technologies used to comply with the proposed Phase 2 standards are expected to be further refinements of the technologies we expect to be used on Phase 1 Large SI engines. For that reason, we are applying the Phase 1 deterioration factors to the Phase 2 engines.[9]

It should be noted that PM is not addressed in the rulemaking process for large SI engines used in recreational marine, commercial, industrial, and other types of equipment and little or no data exist for PM deterioration associated with these types of equipment. Based on EPA's best judgement at this time, PM deterioration has been equated with HC deterioration rates for these types of engines. EPA welcomes any comments or information stakeholder may have concerning PM deterioration.

Table 9 shows the deterioration factors used for recreational equipment, Table 10 shows the deterioration factors used for other large spark-ignition equipment, and Table 11 shows the deterioration factors used for recreational marine engine.

Table 9
Deterioration Factors for Offroad Motorcycles, All-Terrain Vehicles, and Snowmobiles

Equipment/Tech Type	HC	CO	NO_x	PM
Precontrol 2-stroke offroad motorcycles (R12S)	0.2	0.2	0	0.2
Precontrol 4-stroke offroad motorcycles (R14S)	0.15	0.17	0	0.15
Phase 1 4-stroke offroad motorcycles (R14S1)	0.15	0.17	0	0.15
Precontrol 2-stroke all terrain vehicles (R12S)	0.2	0.2	0	0.2
Precontrol 4-stroke all terrain vehicles (R14S)	0.15	0.17	0	0.2
Phase 1 4-stroke all terrain vehicles (R14S1)	0.15	0.17	0	0.15
Precontrol 2-stroke snowmobiles (R12S)	0.2	0.2	0	0.2
Modified 2-stroke snowmobiles (R12S1)	0.2	0.2	0	0.2
Direct Injection 2-stroke snowmobiles (R12S2)	0.2	0.2	0	0.2
4-stroke snowmobiles (R14S)	0.15	0.17	0	0.15

Table 10
Deterioration Factors for Spark-Ignition Engines > 25 HP

Engine Tech Type	HC	CO	NO_x	PM
Uncontrolled				
G4GT25 (gas, 4-stroke, baseline)	0.26	0.35	0.03	0.26
LGT25 (LPG, baseline)	0.26	0.35	0.03	0.26
NGT25 (CNG, baseline)	0.26	0.35	0.03	0.26
Phase 1				
G4GT251 (gas, 4-stroke)	0.64	0.36	0.15	0.26
LGT251 (LPG)	0.64	0.36	0.15	0.26
NGT251 (CNG)	0.64	0.36	0.15	0.26
Phase 2				
G4GT252 (gas, 4-stroke)	0.64	0.36	0.15	0.26
LGT252 (LPG)	0.64	0.36	0.15	0.26
NGT252 (CNG)	0.64	0.36	0.15	0.26

Table 11
Deterioration Factors for Four-Stroke Recreational Marine Engines > 25 HP

HC	CO	NOx	PM
0.26	0.35	0.03	0.26

Note: No deterioration assumed for 2-stroke recreational marine engines.

VII. Liquid Petroleum and Compressed Natural Gas Spark-Ignition Engines

Because liquid petroleum gas (LPG) and compressed natural gas (CNG) engines are primarily four-stroke engines, the EPA decided to assume that they would deteriorate at the same rate as the corresponding gasoline-powered four-stroke SI engines for all pollutants. The EPA is not aware of any deterioration data available for LPG and CNG engines and requests that commenters submit any such data they may have to EPA. If such data become available, EPA will revise the deterioration rates for these engines in NONROAD accordingly.

Endnotes

1. Median life is defined as the midpoint of the scrappage curve at which half of the engines in a given population cease to function and are scrapped. For more information, please refer to the technical report on activity, load factors and median life (NR-005a) and the technical report about scrappage (NR-007a).

2. See endnote 1.

3. U.S. EPA NONROAD Model Technical Report Addenda for Tier 2 Rulemaking Version, March 24, 1999.

4. "Emission Modeling for Recreational Equipment," EPA Memorandum From Linc Wehrly to Docket A-98-01, November 13, 2000.

5. Final Regulatory Support Document: Control of Emissions from Unregulated Nonroad Engines, Chapter 6, Office of Air and Radiation, EPA420-R-02-022, September 2002.

6. "Deterioration Factors for Existing Technology, Gasoline, Outboard Marine Engines," EPA memorandum from Mike Samulski to Chester J. France, Director, Engine Programs and Compliance Division, March 4, 1996.

7. "Revisions to the June 2000 Release of NONROAD to Reflect New Information and Analysis on Marine and Industrial Engines," EPA memorandum from Mike Samulski to Docket A-98-01, November 2, 2000, Docket A-2000-01, Document II-B-08.

8. Proposed Control of Emissions from Nonroad Large Spark Ignition Engines, Recreational

Engines (Marine and Land-based), and Highway Motorcycles, Regulatory Support Document, EPA420-D-01-004, September 2001, Chapter 6.

9. See endnote 8.

Appendix 1

Deterioration Ratio Data for 1969 MY LDGTs